Valuing Low Carbon Energy - Insights for Fusion Commercialisation

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Contents

List of Tables in Main Text[1]

[1] There are additional tables in the annexes.

List of Figures in Main Text[2]

[2] There are additional figures in the annexes.

Acronyms Used in the Text

AMR	Advanced Modular Reactor
BEI	Banking Environment Initiative
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
DEMO	A proposed fusion experimental reactor intended to demonstrate the net production of electricity. Intended to follow on from the ITER project (see below).
EC	European Community / European Commission
EU	European Union
FOAK	First of a Kind
HM	His Majesty's (formerly Her Majesty's)
IAEA	International Atomic Energy Agency
ICO	Imperial, Cambridge and Open
IEA	International Energy Agency
IoP	Institute of Physics.
IPFA	International Project Finance Agency
ITER	International Thermonuclear Experimental Reactor (also Latin for "the way").
JET	Joint European Torus
JT-60	Japan Torus - 60
LCOE	Levelised Cost of Electricity (or Energy)
MIFTI	Magnetic-Inertial Fusion Technology Inc.
Mt	Mega Tonne
MSR[3]	Methane Steam Reformer
MW / $MW_{(e)}$	Mega Watt / Mega Watt (electric)
NEA	Nuclear Energy Agency
NOAK	Nth of a Kind
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
PEM	Proton Exchange Membrane
RAB	Regulated Asset Base
RPI	Retail Price Index

[3] In the literature this technology is often referred to as Steam Methane Reformation (SMR). Methane Steam Reformation (MSR) is used here to avoid confusion with Small Modular Reactors.

SMR	Small Modular Reactor
SPV	Special Purpose Vehicle
TFTR	Tokamak Fusion Test Reactor
UK	United Kingdom
US / USA	United States / United States of America
VaG	Value at Gain
VaR	Value at Risk
WACC	Weighted Average Cost of Capital

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> "If I have seen further, it is by standing on the shoulders of giants"

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Outputs from the PhD to Date

The following outputs from the PhD studies have been published.

Co-editing of the book “Commercialising Fusion Energy – How small businesses are transforming big science” Edited by William J Nuttall, Shutaro Takeda, Satoshi Konishi & David Webbe-Wood. IOP, Bristol. ISBN 978-0-7503-2717-6.

Authorship of the Chapter “Funding and financing of commercial fusion power plants” in “Commercialising Fusion Energy – How small businesses are transforming big science” Edited by William J Nuttall, Shutaro Takeda, Satoshi Konishi & David Webbe-Wood. IOP, Bristol. ISBN 978-0-7503-2717-6.

Co-authorship of the paper Calculations of net present value for a small modular fusion power plant under a range of scenarios. David Webbe-Wood and William J Nuttall. *Proceedings of the Institution of Civil Engineers - Energy*, 1–24. (2023).

Co-authorship of the Cambridge Energy Policy Research Group Working Paper no. 2309, “The Options Value of Blue Hydrogen in a Low Carbon Energy System”. David Webbe-Wood, William J Nuttall, Nikolaos K Kazantzis and Chi Kong Chyong

Potential Future Outputs

Possible future outputs based on the content of this thesis are:

A paper for publication in a journal based on the Cambridge EPRG Working Paper taking into account of comments made on the paper.

A journal paper for based on the work described in Chapter 6.

Abstract

The proponents of nuclear fusion believe that a small modular approach has the potential to achieve a viable source of energy in timescales smaller than those projected for the large scale multinational ITER/DEMO programme. If the numerous technical challenges can be overcome, the question still remains as to whether fusion small modular reactors (SMRs) will be commercially viable. This thesis aims to provide insight into this question and to identify whether approaches other than the generation of electricity to the grid have the potential to increase the value of a fusion SMR or a fleet of SMRs to a developer.

The work has three main components. Firstly, the Net Present Value (SMR) of a fusion SMR supplying electricity for sale to the grid in the UK was evaluated. This showed that there are combinations of electricity prices, capital cost and discount rates that will result in positive NPVs.

In the second component of the work, an existing approach to engineering flexibilities / real options has been extended and applied to the production of hydrogen from methane with carbon capture and storage. The results of this work demonstrate that the application of engineering flexibilities / real options has the potential to increase the value of a project.

In the final stage of the thesis, an engineering flexibility / real options approach has been combined with a portfolio approach to a fleet of fusion SMRs. This demonstrated that this approach has the potential to increase the value of a fleet of fusion SMRs to a developer.

The thesis has demonstrated that it is possible that fusion SMRs may be commercially viable. It has also demonstrated that the use of techniques such as engineering flexibilities and portfolio theory has the potential to increase the value to a developer of a fleet of fusion SMRs based on a tokomak design.

Chapter 1: Overview and Introduction

Overview

The concept of using nuclear fusion for the generation of electricity is not a recent one. The practical development as a large international endeavour has, however, been slow. Recently several proponents have suggested that the commercial implementation of fusion energy can be achieved more quickly by using small modular reactors (SMRs) see for example Meschini and colleagues (Meschini et al., 2023).

Whilst there is uncertainty whether these plans are feasible from a technical standpoint, this thesis is not about technical issues. The core questions to be answered by this research can be put simply as:

> "If small modular fusion reactors prove practical in scientific and engineering terms, will they be practical in commercial terms?"

And

> "Are there financial techniques that a developer of a fusion SMR could use to increase the value of their investment?"

To answer these questions, analyses have been carried out to investigate

- Whether a fusion small modular reactor (SMR) supplying electricity to the UK grid could potentially have a positive net present value (NPV) i.e., give a developer a positive return on their investment?
- Whether the use of engineering flexibilities / real options has the potential to increase the value of an investment?[4].
- Whether the use of engineering flexibilities / real options in conjunction with a portfolio approach will further enhance the value to a developer?

As with all research, the contents of this thesis are based on the work of numerous previous researchers. This work, however, has been extended as described in this thesis and has been applied to novel scenarios. The use of the NPV approach

[4] This analysis was considered in the case of a plant producing hydrogen from methane, but the conclusions are of relevance to fusion SMRs as described in the consideration of portfolios and flexibility.

(Chapter 4) to investigate the financial viability of a fusion SMR supplying electricity to the grid has not, as far as is known, been carried out previously. Whilst the technique is not new the application is novel.

The consideration of the value of engineering flexibilities / real options, (Chapter 5) whilst making use developed by Chyong and colleagues, has extended this approach so that distributions of the possible NPVs can be derived. Having knowledge of these distributions allows more informed decision-making.

Finally, the approach of portfolio theory has been combined with engineering flexibilities / real options, (Chapter 6) to allow the elucidation of the additional value that such an approach could provide to a developer of a fleet of fusion SMRs.

Fusion energy, if it is successfully implemented, has the potential to provide benefits to society which are as not as easily quantified as the return to investors. These include, for example, improvement in energy security, improved grid resilience and reduced radiological impacts when compared to alternative low carbon energy sources.

Introduction

The United Kingdom Government has recommitted itself to the goal of the UK having a zero contribution to global warming by 2050(H. M. Government, 2021). For this to be achieved the UK's energy landscape will need to radically change. This will necessitate the adoption of several new technologies. The use of nuclear fusion to generate electricity and possibly other forms of energy may be one of these technologies.

The concept of using nuclear fusion to produce electricity has been in the background for a long time. However, the practical application of the process has proved to be elusive, In the famous words of *The Economist*, "Viable nuclear fusion has been only 30 years away since the idea was first mooted in the 1950s."(Economist, 2010). The "traditional" approach to commercialisation of fusion has been through Government funded national and international programmes. The current international project is the ITER project involving 35 nations. This is planned to be followed by DEMO a demonstration power plant that is envisaged to produce electricity by 2050 (Nathan, 2019).There are, however, others who believe that the commercial application of fusion can be achieved, in the words of one proponent can be achieved "smaller, quicker, cheaper"

(Gryaznevich et al., 2015). As Meschini and colleagues have noted (Meschini et al., 2023) “Private companies can instead leverage on smaller teams and more effective project management and financial structures to target shorter roadmaps and sooner milestones”.

This approach has received considerable financial support in recent years. McKinsey & Co have reported (Dietz et al., 2022) that private sector investment in fusion has increased from $0.42 billion in the period 2011 to 2015 to $1.5 billion between 2016 and 2020 then to $4.4 billion in 2021 alone. The private sector approach to the commercialisation of fusion is described in Nuttall et al (Nuttall et al., 2020). A recent survey by the Fusion Industry Association (Fusion Energy Association, 2023) reports that the majority of respondents (65 %) believe that commercially viable fusion will be accomplished between 2031 and 2040.

If commercial fusion can be achieved in these shorter timescales is not clear at this time and is not the fundamental question considered in this work. The questions to be answered are, if the technology works as is hoped, does it represent a viable proposition for a commercial operator supplying electricity, or other forms of energy, to the UK economy and are there approaches from engineering flexibility / real options approaches and portfolio theory that would increase the value of an investment in fusion SMRs?. The first route to fusion commercialisation may not be the generation of electricity but the use of neutrons produced. (see Chapter 2).

<u>What is Nuclear Fusion?</u>

At its simplest fusion is the application of Einstein’s famous equation

$$E = Mc^2$$

Two light nuclei are fused together to form a heavier nucleus. However, the mass of the resulting nucleus is slightly less than that of the two initial nuclei. This “lost” mass is converted to energy[5].

There are a number of fusion reactions the most relevant of which are summarised in Table 1.1 below:

[5] In fission reactors, used for current nuclear power, a heavy nucleus is split to form two, or more, lighter nuclei and release energy.

Table 1.1: Some Common Fusion Reactions and the Energy of the Reactions (Conn)

Reaction[6]	Energy Released per Reaction (MeV)
$H + H \rightarrow D + \beta^+$	1.44
$H + D \rightarrow {}^3He$	5.49
${}^3He + {}^3He \rightarrow {}^4He + 2(H)$	12.86
$D + T \rightarrow {}^4He + n$	17.6
$H + {}^{11}B \rightarrow 3({}^4He)$	8.68
$H + {}^6Li \rightarrow {}^3He + {}^4He$	4.023
${}^3He + {}^6Li \rightarrow H + 2({}^4He)$	16.88
${}^3He + {}^6Li \rightarrow D + {}^7Be$	0.113

The first three of these reactions occur in solar processes. The fourth reaction (deuterium, tritium) is the reaction that is attracting the most interest from commercial fusion developers, although some developers are investigating the use of other reactions.

The nuclei involved in fusion reaction both carry a positive electrostatic charge and therefore will repel each other before they can fuse. To overcome this repulsion, it is necessary to give the nuclei sufficient energy and to contain them for sufficient time for a useful amount of energy to be released[7].

For fusion to be sustained the energy released by fusion must be equal to that lost from the system. This was used by Lawson to derive the “Lawson Criterion” (Lawson, 1957). This states that for a sustainable reaction, in the case of deuterium and tritium at a temperature of 10 KeV[8] for a fusion reactor where Q, the ratio of the fusion power to the injected power is 2 and the efficiency of the conversion of the thermal power to electricity is 1/3.

$n\tau\epsilon \geq 10^{20}$ $m^{-3}s$ (Morse, 2018)

Where:

n is the number density of nuclei

[6] D is deuterium, i.e., a hydrogen isotope with a neutron as well as a proton in the nucleus, T is tritium, i.e., a hydrogen isotope with two neutrons as well as a proton in the nucleus. β^+ is a positron and n a neutron.

[7] Alternatively, a pulsed approach can be used where fusion reactions are rapidly repeated.

[8] In fusion studies it is conventional to express temperature in terms of eV. Ten KeV corresponds to approximately 100 million Kelvin.

and $\tau\varepsilon$ the confinement time

Inertial approaches to fusion aim to increase the value of n, whilst magnetic confinement approaches aim to increase the confinement time $\tau\varepsilon$.

An overview of some of the technologies envisaged for the commercialisation of fusion are given in Chapter 2.

Advantages of Fusion

The United States Government Accountability Office (United States Government Accountability Office, 2023) lists the following advantages for fusion energy.

Reduced emissions of CO_2 when compared to fossil fuels.

Result in significantly less radioactive waste than fission power plants.

Does not have the same risk of nuclear accidents as fission plants.

Can be built in locations which are not suitable for renewable energy sources.

Why Small and Modular?

Annex IV of the 2007 IAEA Nuclear Technology Review (IAEA, 2007) defines a small nuclear power plant as one that has an equivalent electrical power output of less than 300 MW. The World Nuclear Association defines a modular reactor as one "designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times" (World Nuclear Association, 2016)

According to their proponents small, modular *fission* reactors have a number of advantages. For example, the then US Secretary of Energy stated.

"Their small size makes them suitable to small electric grids so they are a good option for locations that cannot accommodate large-scale plants. The modular construction process would make them more affordable by reducing capital costs and construction times. Their size would also increase flexibility for utilities since they could add units as demand changes, or use them for on-site replacement of aging fossil fuel plants" (Chu, 2010).

Whilst the arguments above are based on the case of a fission SMR, the same features of the small modular approach are applicable to fusion SMRs.The advantages if factory construction and the production of a large number of units will apply.

Uses of the Energy from a Fusion SMR.

Whilst the obvious use of the output of a fusion SMR is the generation of electricity for sale to the grid this is not the only potential use of the energy. Also, there are other methods of decarbonisation of the electricity system. The nature of fusion reactors with potential output temperature in the range of 500 to 1000 centigrade means that they may have advantages when compared to other technologies when used for some other applications.

The International Atomic Energy Agency (IAEA) has coordinated work on identifying the potential, non-electrical uses of nuclear energy. This has been summarised in three reports (IAEA, 2010), (IAEA, 2013b) and (IAEA, 2013a). Whilst both documents are primarily aimed at applications relevant to *fission* much of the information contained is also appropriate for *fusion* applications as the product from the reactor is the same, low carbon energy which is not subject to problems of interruptability. Similarly, whilst the analyses are based upon "conventional" nuclear power plants there will be applicability to small modular reactors.

The IAEA documents identify a range of possible non-electrical commercial applications for nuclear energy. These are summarised in Table 1.2 below:

Table 1.2: Alternative uses of nuclear energy identified by the IAEA from (IAEA, 2010), (IAEA, 2013) and IAEA (2013a)

Application	Relevant Technologies (where appropriate).
Oil and gas extraction (tertiary oil recovery)	
Oil upgrading and refining	Steam cracking Super heating Naphtha extraction
Ethanol production	
Ethylene production	
Hydrogen production	High temperature water splitting Methane Steam Reforming Advanced Methane Reforming Biomass gasification

	Electrolysis of water
Steel production	
Aluminium production	
District heating	
District cooling	
Desalination	Multi-effect Distillation (MED) Multi-stage Flash (MSF) Reverse Osmosis
Wood cooking / paper production	
Cardboard production	
Plastic film production	
Greenhouse horticulture	
Salt refining	

As well as the options identified by the IAEA other potential use have been suggested. It has been proposed that the output from a fusion power plant is used to remove CO_2 from the atmosphere (Nam & Konishi, 2019). This method uses the heat from a fusion reactor to convert lignin and cellulose in biomass into charcoal, which can be stored indefinitely and hydrogen which can be used to produce electricity via a fuel cell. Central to the economic assessment of this proposal will be the earning of carbon credits from the removal of CO_2.

As pointed out by Nuttall (Nuttall, 2023) another potential application of fusion technology is a source of neutrons. These neutrons would be used for industrial radiography, and the production of medical isotopes using transmutation (Nuclear Engineering International, 2023) and (Astral Systems, 2023). One developer of this technology believes that there will also be applications in the transmutation of nuclear waste (Shine, 2023).

Details of the technology of some of these alternative uses are discussed in more detail in Chapter 2. Not all of these applications are likely to be appropriate for use in the circumstances of the UK in the mid-part of the current century. Whilst a number of technologies which, it has been suggested, could be employed to make use of the energy produced by a fusion SMR have been described no attempt has been made in this thesis to assess whether they are feasible or to attempt to identify which may be the best option.

Financial Assessment Techniques.

At a technology level, the financial assessment of an energy generation capability is performed by using a Levelised Cost of Energy (or electricity) (LCOE) approach. This is defined by BEIS (BEIS, 2020) as being “the ratio of the total costs of a generic plant to the total amount of electricity generated over the plant lifetime”. The assessment of individual plants is generally carried out by making single-point estimates of the Net Present Values. This thesis examines these approaches and seeks to augment them with more sophisticated methods.

Numerous techniques exist to enable the assessment of the financial merit of a technology and to identify approaches that have the potential to increase the value of a project using the technology to a developer. Three approaches have been considered in this thesis. These are:

Use of the Net Present Value

The use of engineering flexibility and real options

The use of portfolio theory

These approaches are outlined below:

<u>The Concept of Net Present Value (NPV)</u>

The principle behind the concept of NPV is that the value of money at some time in the future is not the same as the same amount today. The value of money in the future is less than its current value. This reduction of the future value of money reflects both the fact that the money could have been invested elsewhere and the fact that there is a risk that the money won’t be repaid. It also reflects the preference for gratification in the near future rather than in the remote future. The NPV is calculated by discounting cash flows, whether income or expenditure, occurring in the future according to the equation.

$$NPV = \frac{C}{(1+R)^T}$$

Where C is the cash flow (either positive or negative)

T is the time period in which the cash flow occurs and

R is the discount rate.

The total NPV of the project is then simply the sum of all these discounted cash flows through to the end of the project. The concept of NPV typically avoids the need to consider inflation. All the calculations are carried out using financial data relevant to a fixed time. Discounted cash flow techniques, of which calculation of the NPV is an example, have drawbacks. Locatelli and colleagues (Locatelli et al., 2020) have outlined some of these:

> The stochastic nature of some of the cash flows is not always accounted for[9].
>
> The choice of discount rate is, to a degree, arbitrary.
>
> No account is taken of the ability of managers to respond to changing circumstances.

The concept of NPV has also been criticised by, amongst others, McSweeney (McSweeney, 2006). He contends that the use of the NPV can bring benefits, however, when the unavoidable uncertainties are supressed and excessive faith is placed in the results the consequences can be damaging. Conversely Connor (Connor, 2006) suggests that these consequences are a result of the behaviours and competences of decision makers rather than a problem with the method.

To minimise these limitations other techniques have been developed and are outlined below and used in the later chapters.

<u>Real Options and Engineering Flexibilities</u>

Trigeorgis (Trigeorgis, 1996) describes the use of real options as giving "the potential to conceptualise and quantify the value of options from active management and strategic interactions". The values of these are embedded in capital investment opportunities. He identifies the options as taking the form of decisions such as:

- Defer investment in project until conditions are more favourable
- Option to default at stages during construction
- Stop or pause asset deployment
- Changing scale by expanding or contracting
- Abandon project and sell for salvage value

[9] In the approach used in this work some account is taken of the stochastic nature of some of the income and cost streams.

- Switch inputs and / or outputs
- Corporate growth options
- Carry out research and development to capitalize on future technologies

In addition to these generic options the application of any technology will bring the possibility of applying engineering flexibilities that are specific to the technology and marketplace. Cardin has proposed (Cardin, 2013) a strategy for identifying and incorporating flexibilities into an engineering design. This staged approach is applied to the case of a fusion SMR in the text box below:

Phase 1 Baseline design

Baseline designs are developed using a range of techniques such as those described by Tomiyama and colleagues (Tomiyama et al., 2009). Some techniques are more suited than others for use in developing engineering flexibilities. Once these baseline designs have been developed, they can be expanded and enriched by consideration of uncertainly and variability in subsequent phases.

Phase 2 Uncertainty recognition

A fusion SMR will, like any engineering system, will experience a changing economic environment over their lifetimes. What may be the most attractive use of the energy at the start of the plant's lifetime may not be the most attractive at a later date. Identification of the sources of these uncertainties and the impact that they will have on performance need to be identified.

Phase 3 Concept generation

Once the uncertainties, and their impacts have been identified and quantified the baseline designs developed in phase one are examined to evaluate how they will adapt in the face of the uncertainties identified.

Phase 4 Design space exploration

Once the concepts enabling flexibilities have been identified, quantitative methods are used to identify those concepts which offer the greatest value. A range of techniques are available for carrying out these assessments.

Assessing the value of the Engineering Flexibilities

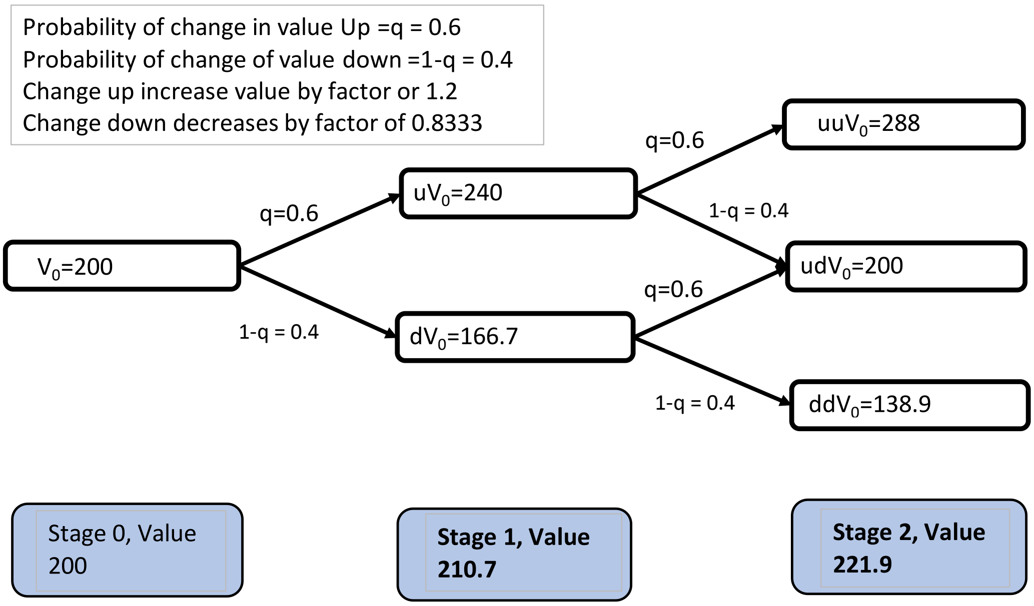
The incorporation of engineering flexibility into a design and its construction will entail costs. It however has the potential to allow the owner to receive increased income when compared to the original (non-flexible) concept. Changes in the market conditions and/or wider economic and policy environment *may* make it beneficial to switch the output from electricity generation to another use of energy (or back to the generation) of electricity. There is an *option*, but not an *obligation* to take advantage of this flexibility. The value of the facility may be viewed as consisting of a stream of cash flows and a set of options(Tomiyama et al., 2009). This engineering flexibility gives the owner a Real Option associated with the ability to make use of the engineering flexibility. A Real Option differs from a financial option in that they involve tangible assets rather than financial instruments.

Amram and Kulatilkala (Amram & Kulatilkala, 1999) identify a range of methods for valuing these options. Financial options (as distinct from real options) are valued by making use of the Black-Scholes equation[10]. In this approach a partial differential equation which relates the value of the option to the value of the asset, the volatility of the value of the asset and the time remaining until the option may be exercised is developed. This equation may be solved by analytical means, the use of analytical approximations or the use of numerical solutions. However, the use of the Black-Scholes method is not generally appropriate to the valuation of real options as there is no underlying (traded) asset to which the value of option can be related (Amram & Kulatilkala, 1999). Secondly the underlying real asset (in this case, the power plant) is controlled by the management who can decide whether to exercise the option.

One alternative approach, that is more appropriate to the valuing of real options is the use of binomial lattices (see for example Copeland and Antikarov (Copeland & Antikarov, 2003)). In this approach the value of the Real Option is calculated at the start of the time step (generally a year). The value of the option at the end of the period is calculated in the case in which the option is exercised and the case in which it is not exercised. The probabilities of the flexibility being exercised and not being exercised are also calculated. The process is then repeated for the next time step with the two possible outcomes from the first step being taken as the starting point to give possible values and associated probabilities. This process is illustrated (for a simple case) in figure 1.1 below.

[10] More accurately the Black-Scholes-Merton equation.

Figure 1.1. Illustrative binominal lattice of a real option value



This process is repeated for all the time steps[11] until the end of the lifetime of the plant. The value of the plant is then the expectation value[12] of possible end state values. The value of the flexibility is the difference between this value and the value of the facility without the flexibility. However, as Cardin (Cardin, 2013) points out binominal lattices are limited in their ability to take account of complex decision rules.

Another method for valuing the engineering flexibilities in the design is to make use of a simulation approach making use of Monte-Carlo techniques. In this approach the decision whether to take advantage of a flexibility is made at the start of each time period based on decision rules. These rules describe which course (invoke the flexibility or not) to take based on which option it appears that will give the greatest income. Which option is the most profitable will depend on the value of model parameters such as the cost of inputs and the prices of possible outputs. The values of these are represented by distributions (either continuous or discrete) and the model randomly selects from these distributions before applying the decision rules and then calculating the value. This process is

[11] In reality decisions whether to switch between uses of the energy are being taken continuously. The use of discrete timesteps is an approximation to this.
[12] i.e., the sum of the values of the product of each value and its probability of being achieved.

repeated a large number of times resulting in a distribution for the value of the plant. This approach is used in this thesis (Chapter 4).

Relevant Real Options Studies**.**

Santos and colleagues (Santos et al., 2014) have used a real options approach to renewable energy projects and concluded that the use of flexibilities increases the value of the projects. Similarly, Martínez-Ceseña and Mutale (Martínez-Ceseña & Mutale, 2011) have used a real options approach to hydroelectric projects and shown that this approach increases profitability. This conclusion was also reached by Shi and Song (Shi & Song, 2013) in their analyses of large nuclear projects in China.

Locatelli has with various colleagues carried out studies incorporating real options in the analysis of fission SMRs. These have shown that (Locatelli et al., 2014) the "wait and see" option presented by SMRs is a useful attribute. The work also demonstrates that the presence of real options makes SMRs favourable in comparison to large reactors. It has also been demonstrated that desalination in conjunction with a fission SMR is a realistic approach to making use of the output at times where electricity demand is low, whilst avoiding the need to reduce the output of the reactor output (Locatelli, Boarin, et al., 2015)

Locatelli has also with colleagues (Locatelli, Palerma, & Mancini, 2015) shown that the ability to operate energy storage plants with the flexibility to be used for reserves purposes and for market arbitrage increases the value of the plants. Cardin and colleagues (Cardin et al., 2017) have shown using a real options approach a nuclear power programme can obtain additional value from using the flexibilities of staging, expansion and life extension to increase value. He and colleagues (Cardin et al., 2012) have also analysed an accelerator driven sub critical fusion reactor to show that incorporating flexibility in the design increases the value of the power plant.

Portfolio Theory

The academic study of portfolio theory is generally held to have been initiated by Markowitz (Markowitz, 1952). However, as he points out (Markowitz, 2009) the concept of the use of portfolios to minimize risk was well known prior to this, at least at an intuitive level. As Antonio states in The Merchant of Venice:

> "My ventures are not in one bottom trusted,
> Nor to one place; nor is my whole estate
> Upon the fortune of this present year;
> Therefore, my merchandise makes me not sad".
> (Shakespeare, 1598)

Markowitz posits that "an investor does (or should) consider expected return a desirable thing *and*[13] variance of return an undesirable thing.". However, the portfolio with the greatest return is not necessarily that with the lowest variance. He postulates that there may be statistical techniques by which, for portfolios of financial securities, efficient combinations of return and variance can be obtained. Since then, much has been done to develop portfolio theory approaches in the financial world. Shimon Awerbuch applied and adapted these techniques to energy systems (O'Connor, 2008). The current state of the art is summarised in texts such as that of Elton and colleagues (Elton et al., 2014).

However, the application of portfolio theory to financial markets is not considered further here. Several authors have applied portfolio theory to the consideration of energy systems. Jansen and Beurskens (Jansen & Beurskens, 2008) considered the application of portfolio theory in the selection of energy technologies to be used in the Netherlands in 2030. They conclude that diversification of the technologies, particularly the inclusion of renewable technologies, can reduce the risk by 20% when compared to a baseline case at no extra cost. Awerbuch and Yang (Awerbuch & Yang, 2008) have used portfolio theory to value investments in power generation. They conclude that using a portfolio approach benefits the decision maker in that only portfolios which lie on the efficient frontier need further consideration. It also reduces the risk.

Roques and colleagues (Roques et al., 2008) have made use of Monte-Carlo techniques to study the mix of coal, gas and nuclear generation for the UK grid. Their work shows that using inputs reflecting the UK's historical circumstances results in a portfolio largely composed of gas plants, reflecting the observed situation, largely as a result of the high correlation between gas and electricity prices. The work also demonstrates that if long term fixed price power purchase

[13] Italics in original.

agreements were available the portfolio would be more diverse. Adams and Jamasb (Adams & Jamasb, 2016) have extended the work of Roques and colleagues to consider the circumstance pertaining in 2016. They conclude that coal should not form part of the portfolio and that the inclusion of wind generation would increase the value of the portfolio. Locatelli and Mancini (Locatelli & Mancini, 2011) have used portfolio theory to investigate the mix of small and large power plants (using different technologies) best for a power grid. They conclude that to maximise the return and reduce the risk, the portfolio needs to contain several types of power plants and that in the case of a small grid, this mix should include small plants.

As outlined above there are a range of techniques that can be used to evaluate the commercial viability of fusion SMRs and a range of “products” they can be employed to supply. Prior to the employment of some of these techniques it is necessary to consider the technologies and the environment in which it is envisaged that they are deployed.

References Chapter 1

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Chapter 2: Technologies and Scenarios Considered in the Thesis

The work in this thesis seeks to extend and combine techniques used to assess the financial variability of energy products and to apply them to the case of a fusion SMR.

This application to the case of a fusion SMR is in three stages. Firstly (Chapter 4) the concept of NPV is used to assess the financial performance of a fusion SMR supplying electricity to the UK grid. The application of the NPV techniques incorporates a probabilistic approach to the reliability of the plant.

Secondly (Chapter 5) the work of Chyong and colleagues (Banking Environment Initiative, 2012) has been applied to a different technology and extended to make use of a Monte-Carlo approach. This enhancement enables distributions of the value of the engineering flexibilities / real options to be derived and hence statistics of the distributions to be calculated. This contrasts with the usual approach where only a single value of the option is calculated.

Finally (Chapter 6) the Monte-Carlo approach to the valuation of engineering flexibilities / real options described in Chapter 5 is combined with a portfolio approach to investigate the economic performance of a fleet of fusion SMRs some of which have the flexibility to be able to be retrofitted to produce alternative "products".

Prior to these analyses the "energy environment" in which the plants are postulated to be operated is described. Also, the technologies considered in the assessments are outlined (this Chapter). A discussion of how the developer of a fusion SMR may obtain finance and possible sources of income is given in Chapter 3.

The thesis attempts to answer the questions:

- If small modular fusion reactors prove practical in scientific and engineering terms, will they be practical in commercial terms?
- Are there financial approaches that can enhance the value of a fusion SMR plant to a developer?

Future UK Energy Environment

The assessments carried out in this thesis assume that the fusion SMRs, and the other plants are located in the UK, and thus the future UK energy environment are relevant. A fusion SMR operating in the UK for a lifetime of sixty years starting generation circa 2040 will be supplying an energy market that will be different to that pertaining today. The Committee on Climate Change (CCC) has called for the UK to reduce its emissions of greenhouse gases to “net zero” by 2050 (Committee on Climate Change, 2019). This recommendation has been incorporated into law (Parliament, 2019).

The CCC believe that this aim is achievable by, *among other things,* the continuing use of nuclear power for energy generation and the use of hydrogen to replace oil, coal and natural gas in industrial applications and in transport(Committee on Climate Change, 2019).

Jenkins and colleagues (Jenkins et al., 2018) have reviewed over 40 studies on the impact of “deep decarbonisation” on the power sector. They conclude that paths that rely extensively or even entirely on variable renewable energy (principally solar and wind) face greater challenges related to the inefficient use of resources, lower decarbonisation costs etc. than alternative paths that include a wider mix of low carbon (such as nuclear, geothermal and the use of fossil fuels with CCS).

The CCC has also called for no new houses to be connected to the gas grid after 2025 (Committee on Climate, 2019). This recommendation was agreed upon by the then Chancellor of the Exchequer in the 2019 Spring Statement (H. M. Treasury, 2019). These changes in the possible future UK energy environment mean that there is likely to be a greater demand in the future for hydrogen.

The CCC also speculate that there may be a role for the use of technologies that remove and sequestrate CO_2 in conjunction with the generation of electricity. One such technology making use of fusion energy in conjunction with biomass has been proposed (Nam & Konishi, 2018)

A Brief History of Fusion Energy

Kendl and Shukla (Kendl & Shukla, 2011) have given a brief history of the research into controlled fusion. This is briefly summarised below.

In 1920 Arthur Eddington suggested that the sun derived its energy from the conversion of hydrogen to helium. The first quantitative theory of stellar fusion energy generation was proposed by Hans Bethe in 1939.

In 1938 Kantrowitz and Jacobs made the first attempt to build a magnetic confinement fusion reactor in an unofficial experiment at Langley (USA). However, these experiments had to be abandoned when management became aware of them.

During the 1950s, experiments were carried out in the USA and UK on stellarator, magnetic pinch and inertial confinement techniques. The first tokamak[14] was developed at the Kurchatov Institute in the Soviet Union. This led to the construction of large tokamaks at Princeton in the US (TFTR), Culham in the UK (JET) and Tokai in Japan (JT-60).

Following the 1985 Gorbachev - Reagan summit, the decision was made to initiate the ITER project and construction work started at Cadarache in France and is continuing. However, numerous private sector companies are pursuing alternative approaches.

Approaches to Fusion Energy

Pearson and Takeda (Pearson & Takeda, 2020) provide a useful overview of the approaches to the commercialisation of fusion energy. Brief details of some of the approaches under development are given below. These are selected to give an indication of the range of approaches. No attempt has been made, within this thesis, to assess which of these approaches has the greatest chances of success (if any)[15].

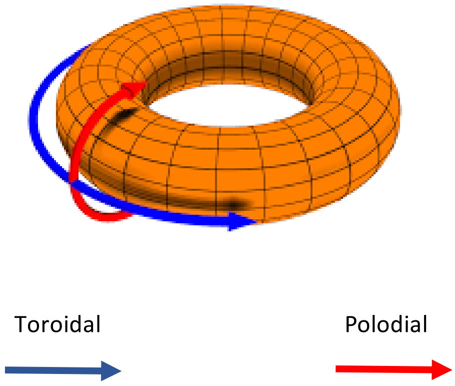
Magnetic Confinement Approaches

Tokamak Energy (Tokamak Energy, 2023) is developing a spherical tokamak using high temperature superconductors. In this approach, the plasma, rather than being in a “doughnut” shape as in a conventional tokamak, is in a shape more akin to that of a cored apple. This is held to provide a more efficient confinement of the plasma.

[14] This name is derived from a Russian acronym meaning toroidal chamber with magnetic coils.
[15] Or whether any of the approaches of organisations not considered here will succeed

In a tokamak, magnetic fields are provided by external coils confine the plasma. One set of coils provide a toroidal magnetic field. A central solenoid provides a poloidal field. Toroidal and poloidal directions are illustrated in Figure 2.1 below. The interaction of these two magnetic fields results in a helical field which confines the plasma.

Figure 2.1 Toroidal and Poloidal Directions



Adapted from (Burke, 2006) and reproduced under the terms of the Wikimedia Creative Commons Licence https://creativecommons.org/licenses/by-sa/3.0/deed.en

Renaissance Fusion (Renaissance Fusion, 2023) are developing a stellarator design making use of high temperature superconductors. Stellarators differ from tokamaks in that there is no central solenoid and hence no poloidal field. Instead, they rely on complex designs of the external coil magnets. This, it is claimed, results in a design that is simpler to operate and more efficient because no current is induced in the plasma. Conversely, the design of the magnetic coils is more complex. Renaissance Fusion believe that they have overcome these drawbacks.

<u>Inertial Confinement Approaches</u>

First Light Fusion (First Light Fusion, 2023) are developing an inertial approach to fusion energy. In their concept, a high velocity projectile is fired electromagnetically at a target. This target consists of two components, an amplifier and a fuel capsule. The amplifier, when struck by the projectile, boosts the pressure that impacts on the fuel capsule. It also ensures that the shock wave converges, and the fuel capsule is compressed from all sides so that a density sufficient for fusion is achieved.

The interaction of the target and the projectile occurs in a fuel chamber with flowing liquid metal walls, thus reducing the material engineering problems associated with neutron irradiation.

Focused Energy (Focused Energy, 2023) are investigating an approach based on laser implosion. In their approach a target containing the fusionable material in a plastic and metal shell is subject to long and short laser pulses. A short pulse is directed at a gold foil in the shell. This foil is thus converted into an ion beam which is injected into the fuel. A longer duration laser pulse is used to compress the fuel.

Magnetic- Inertial Approaches

Magnetic-Inertial Fusion Technologies (MIFTI) (Magnetic-Inertial Fusion Technologies) are using a Z-pinch approach. In the Z-pinch approach an electrical current is used to generate a magnetic field in the plasma. This field then compresses the plasma ("pinches it"). In MIFTI's approach a hohlraum with a high atomic number liner and fuel in the centre is used. The liner implodes to form a shock wave in the target plasma thus heating it. The energy from the fusion is collected from released neutrons in a flowing liquid lithium wall. In the case of an aneutronic[16] fusion the charged particles would be collected directly to produce an electrical current.

Further details of the approaches of the companies mentioned above, and of other companies are given by Pearson and Nuttall (Pearson & Nuttall, 2020). More extensive lists of private sector companies involved in fusion commercialisation are provided by Fusion Energy Base (Fusion Energy Base) and by the Fusion Energy Association (Fusion Energy Association, 2023). For further details of the physical principles behind fusion and these approaches can be found in Morse (Morse, 2018).

Technical Challenges to the Commercialisation of Fusion Energy

The US Government Accountability Office (United States Government Accountability Office, 2023) has identified some areas where there are still scientific and technical challenges to be overcome in the commercialisation of fusion energy. These are:

Lack of full knowledge of the behaviour of burning plasmas.

[16] That is a fusion reaction which does not release neutrons.

The need to develop materials better able to withstand the conditions experienced with a fusion reactor for extended times.

Development of better techniques for the extraction of fusion by-products from the plasma.

Further development of plasma facing systems that can be easily maintained and replaced.

Resolution of issues concerning the supply, security and safety of tritium.

Whilst as described above there are different technological approaches being pursued by proponents of fusion commercialisation, and within these approaches different sizes of plant under consideration, this work considers only one approach. This is a fusion tokomak SMR consisting of either one or two units designed to produce 175 $MW_{(e)}$ per unit. The choice of the size and design is based solely on the fact that this is the configuration that the developer who provided the data is considering. No attempt has been made in this work to ascertain whether other sizes and configurations would give different results.

The work presented here is primarily concerned with the development and application of techniques for assessing the commercial viability of fusion SMRs. It does not attempt to determine which of the approaches is likely to give the best return to an investor or is likely to be the first to be implemented.

Other Technologies Used in the Work

As stated in Chapter 1, the production of electricity for sale to a grid is not the only “product” that a developer of a fusion SMR can sell to provide a return on their investment. It is possible that the return associated with an alternative product, or combinations of products will give a greater return. This is discussed in Chapter 6.

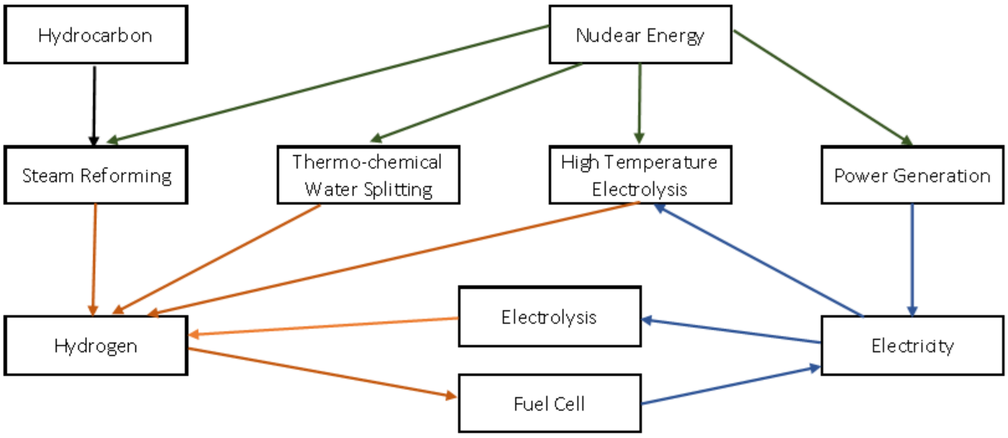
A list of the possible products is given in Chapter 1. The consideration of all these potential “products” would be impractical within the context of this work. Two products have been considered, the production of hydrogen and the sequestration of CO_2 from biomass.

Hydrogen production

Reviews of methods of hydrogen production have been produced by, amongst others, the IAEA (IAEA, 2013) and Samanta and Verma(Samanta & Verma, 2015).

The IAEA has identified a range of techniques by which nuclear power can be used to produce hydrogen. These are summarised in Figure 2.2 below:

Figure 2.2: Schematic of the approaches to producing hydrogen using nuclear energy (redrawn from IAEA (IAEA, 2013))



Two of these approaches to the production of hydrogen were considered within this work; Methane Steam Reformation (MSR) and the electrolysis of water using a Proton Exchange Membrane (PEM).

Methane Steam Reformation

The Methane Steam Reforming process is the leading technology for producing (IEAGHG, 2017). The process consists of a number of stages:

The feedstock is initially purified to remove chlorine and sulphur compounds and olefins[17].

In the steam reforming stage, the methane is reacted with steam in the presence of a catalyst to produce carbon monoxide and hydrogen according to the reaction.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

The conversion efficiency of this process is improved with increasing temperature and steam/methane ratio in the feedstock.

The water shift reaction then takes place by which the carbon monoxide is reacted with steam.

[17] Compound with the formula C_nH_{2n}

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Finally, the hydrogen is purified using a pressure swing adsorption process in which the impurities are removed by adsorption on material such as zeolites, activated carbon or silica and aluminium gels to produce a high purity (99.999%) hydrogen stream.

PEM Electrolysis

The technique of PEM was initially developed by Grubb in the 1950s (Grubb, 1959) and further developed by the General Electric Co. (Russell et al., 1973). In this technique, water is provided to the anode, where it is decomposed into oxygen, a hydrogen ion (proton) and an electron. The hydrogen ion is transported through the membrane to the cathode. The electron travels via the electrical circuit to the cathode, where it recombines with the hydrogen ion to produce an uncharged hydrogen atom.

Kumar and Himabindu (Kumar & Himabindu, 2019), in a review of the technology, describe the advantages of this technology as compact equipment, high efficiency (80% to 90%) and high purity of the hydrogen produced (99.99%).

<u>Carbon Sequestration</u>

Konishi and colleagues (Konishi et al., 2018) and (Nam et al., 2020) have described the use of fusion technology to sequestrate CO_2 by producing charcoal from biomass. In this concept, a fusion reactor is coupled, via a heat exchanger, to a pyrolysis chamber in which biomass (assumed to be wood in this concept) is heated in the absence of oxygen to produce carbon according to the formula

$$C_6H_{10}O_5 + H_2O \rightarrow 6H_2 + 6CO$$

The resulting carbon can then be used as a soil conditioner (biochar) or stored. The income streams for this process are from the sale of the biochar and credits for the CO_2 that would have been released into the atmosphere had the biomass not been treated.

<u>Generation of Electricity for Supply to the Grid</u>

The “baseline” application of the energy from a fusion SMR is the supply of electricity to the grid. This is achieved by the use of the heat generated to produce steam[18] . This steam is used to operate a turbo-generator to produce electricity for

[18] There are alternative approaches that directly capture charged particles produced in the fusion reactors.

sale to the grid. This electrical energy can be either provided as a baseload supply or used in a load following capacity.

Sequestration and hydrogen production were used as the alternative technologies (instead of electricity generation) as the data necessary for the calculations were relatively easy to obtain. No attempt has been made in this thesis to ascertain whether different alternative technologies would provide better returns.

Methane Steam Reformation was considered for the work described in Chapter 5 as the variability of the prices for natural gas (methane) and the cost of CO_2 releases to the atmosphere are those factors that determine whether the options are exercised and hence give value to the engineering flexibilities. PEM was used as the technology for the production of hydrogen described in Chapter 6 as the value of the hydrogen produced will not be impacted by these factors.

Prior to the consideration of these technologies in conjunction with the appraisal techniques outlined in Chapter 1, Chapter 3 considers the sources of funding that may be available to any developer of fusion SMRs.

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Chapter 3: Funding and Financing Commercial Fusion Plants

The work presented in this chapter is closely based on Chapter 4, Funding and financing commercial fusion power plants. In W. J. Nuttall, S. Konishi, S. Takeda, & D. Webbe-Wood (Eds.), *Commercialising Fusion Energy: How small businesses are transforming science* (pp. 4-8). Institute of Physics Publishing. https://doi.org/10.1088/978-0-7503-2719-0. Whilst this chapter was written by myself it has benefitted from comments by my co-editors and from the anonymous referee(s).

Introduction

Whilst the question of whether small-scale fusion reactors can be made to work from an engineering and technological standpoint is considered in other chapters 4, 5 and 6, this chapter considers the question whether such an endeavour would make sense from a financial or economic point of view. Any approach to commercial fusion will require substantial investment. This investment will not be forthcoming unless those providing the investment (whether governments, companies, or others) believe that a benefit is likely to be received in return. This benefit need not be financial but may be another form of societal good. For all investors, an early return is preferable to one received later. However, as described by Offer (Offer, 2018) different parties will have different time horizons and the requirement of a commercial organisation for a quick return means that some form of support from the Government may be required.

The current 'mainstream' international approach to commercial fusion is large scale and involves multiple partners. It is possible that small-scale approaches will be more amenable to attracting the necessary investments. However, proponents of commercial projects believe that commercialisation can be achieved with a 'smaller, quicker, cheaper' approach (Gryaznevich et al., 2015). It is possible that this approach will be more attractive to investors.

In comparison with some other methods of energy generation, nuclear energy, whether fission or fusion, suffers from the problem that major expenditure is required during the construction phase and then less expenditure is required during the operational phase when income from the sale of the energy (via whatever means) is received. This means that the cost of capital is a significant contribution to the overall costs. Compact reactors have been proposed (Office of Nuclear Energy, 2016) as one means of reducing the costs of capital i.e. the minimum return required to justify undertaking the construction of the plant, in the case of fission reactors and is an approach that has attracted subsidies from Governments (e.g., the United Kingdom Advanced Nuclear Technologies programme (BEIS, 2018)

Proponents of compact reactors describe the advantages as:

Small modular reactors offer a lower initial capital investment, greater scalability, and siting flexibility for locations unable to accommodate more traditional larger reactors. They also have the potential for enhanced safety and security compared to earlier designs (Office of Nuclear Energy, 2016).

In particular, the use of a modular approach enables much of the fabrication to be carried out in factory conditions, with the consequent increase in efficiency. The deployment of a fleet of power plants of the same design will also lead to savings as a result of learning effects. These effects are the result of the repetition of the tasks involved with the construction of the modular plants leading to reduction in the time required and hence costs.

The concept of SMRs (for fission) does not have universal acceptance. Ramana (Ramana, 2015) gives an overview of the history of small reactors and uses this story to question the assumption of proponents that SMRs will have economic advantages over large reactors. With Ahmad (Ramana & Ahmad, 2016) he considers the case of Jordan, which has been mooted as a possible market for fission SMRs and concludes that they would not be a good choice for Jordan for reasons such as public acceptance of multiple sites and the need for additional cooling water for the same energy output compared to a large reactor as well as the posited higher costs. If such obstacles were to prove insurmountable any investment in plant design and other preparatory activities would be lost.

Lindley and colleagues (Lindley et al., 2023) have considered the economic viability of fusion plants and have concluded that to become commercially viable there will need to be reductions in the costs of the vessel and magnet systems, improvements in component lives, availability and standardisation. They also state that fusion power plants should be considered as a programme and not as individual plants/projects. They also call for an appropriate regulatory environment which recognises the reduced risks when compared with fission plants and that regulations should be standardised internationally to prevent the need for repeated amendments to designs. In the UK the Government has indicated (Government,

2023) that it intends to introduce for fusion plants a licencing regime that does not mirror that of the regime for fission power plants.

Fusion SMRs, being baseload generators, will not give rise to the additional costs to the grid system costs that result from the presence of variable renewables on the grid. The OECD (OECD, 2019) estimates that these additional costs are approximately £20per MWh for a system with 50% variable renewables rising to £40 per MWh for 75%.

Possible sources of funding

Even a small-scale fusion power plant will require a significant capital investment. Bechtel and collaborators (Bechtel National Inc et al., 2017) have estimated the overnight capital cost[19] of a 10th of a kind fusion generation plant with an output of 150 MW(e) to be in the range of $0.7–$1.9 billion[20]. These costs (and the costs of capital) will have to be provided prior to any income being received. There are a number of possible sources for this investment. Whichever source provides the capital investment, it will need to be confident that there is a reasonable likelihood of a return on its investment. For a commercial investor this return will be financial. Governments will, however, take a wider societal perspective in which “all costs and effects should be included regardless of who experiences these” (Dorst et al., 2017). In this case the effects which a government may consider as benefits include reductions in CO_2 emissions, increased energy security or providing support to a technology with potential for export earnings.

There is however disagreement within the economics community as to whether these additional societal benefits that a lower discount rate should be used. Greco and Moszoro (Greco & Moszoro, 2023) have reviewed the literature and report that the literature supporting a lower discount rate is “vast and robust”. However, they also report that the same applies to the literature supporting the use of the same discount rates that are used by private investors. The authors go on to suggest that a lower rate should be used because societal benefits whilst risky are predictable, whereas financial benefits are unpredictable.

[19] That is the costs excluding the costs of capital.
[20] 2016 dollars

Provision of funds by a commercial operator

A large utility company might consider a compact fusion reactor as a part of its portfolio of energy generating assets. Any proposal to invest funds will have to compete with other proposed uses of the utility company's funds[21]. These alternative proposals may well include compact fission reactors which share many (but not all) of the advantages of compact fusion reactors. As suggested by Zablielski (Zabielski, 2019) the attractions of using proven technologies may mitigate against the selection of fusion. This investment by a commercial company could be carried out through the use of a special purpose vehicle (SPV). As described by Sainati and colleagues (Sainati et al., 2017) and (Steffen, 2018) a special purpose vehicle is a fenced entity which enables the isolation of the assets, liabilities and risks within the vehicle. The vehicle also provides the project with remoteness from the risk of bankruptcy of the parent organization. The SPV is financed without (or with very limited) guarantees from the sponsors, such that lenders to the SPV depend on future project cash flows only and cannot recourse on the sponsor's other businesses.

Funds provided by a bank or similar investor.

Alhamdan and colleagues (Alhamdan et al., 2023) have recently (late 2022) surveyed the state of fusion commercialisation. They report that the initial investments have come from investment companies (including venture capital, private equity and family offices) and from corporations in the energy sector, such as Cenovus (Canada), ENI (Italy), Equinor (Norway) and Chevron (USA). Funding has also been received from two Sovereign Wealth Funds (Singapore and Malaysia) and from Very High Net Worth individuals who have stated that their investment was not motivated by profit.

Microsoft have recently (May 2023) agreed to obtain electricity from Helion's first fusion reactor (Helion, 2023). This (50 $MW_{(e)}$) plant is scheduled to be begin operations in 2028 and the agreement is part of Microsoft's ambition to be carbon-negative by 2030.

In their 2023 survey the Fusion Energy Association (Fusion Energy Association, 2023) has reported that the industry had attracted \$6 Bn an increase of \$1.6 Bn since their previous survey.

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[21] i.e., there will be an opportunity cost.

Landberg and colleagues (Landberg et al., 2019) report that the global total of assets under management was $92 trillion in 2018 and that at least $30.7 trillion of this was held in green or sustainable investments, an increase of 34% since 2016. Whilst small-scale fusion may appear to be a suitable recipient of such investments there is, as Landberg *et al* point out, still no consensus as to what constitutes a 'green' or 'sustainable' investment. If nuclear fusion were to be included in a taxonomy of sustainable investments, it is possible that a developer would be able to obtain funding from green investment sources.

The European Union has developed an action plan on sustainable finance. As part of this action plan, an expert group has been established to develop a taxonomy of appropriate technologies. The EU Expert Group (E. U. Technical Expert Group on Sustainable Finance, 2019) initially excluded nuclear energy from their taxonomy of technologies that aim to provide performance criteria for those bodies wishing to access 'green funding'. This exclusion is justified on the basis of the lack of final disposal routes for spent fuel. However, following an assessment by the European Commission's Joint Research Centre (Joint Research Centre, 2021) the final version of the taxonomy (EU (2022) does contain nuclear fission, subject to certain conditions. This is, however subject to legal challenges (Euronews, 2023).
The Expert Group state that fusion (together with other technologies that are currently at low Technology Readiness Levels) may be added to the taxonomy in the future. Whether this updating of the taxonomy will occur and whether the timescale will be such that it benefits the development of small-scale fusion remains to be seen.
The EU also hopes that their taxonomy will impact on investors outside the EU. This absence of fusion from the taxonomy may make fusion ineligible to access 'green funding' more widely.

The UK's recently published Mobilising Green Investment document (HM Government, 2023) states that the Government proposes that nuclear energy will be included in the UK Green Taxonomy on which it envisages starting consultation in autumn in 2023. It does not however specify whether nuclear in this context comprises both fusion and fission or is limited to fission.

It is not clear, however, whether the inclusion of nuclear energy in such taxonomies will have any significant effect. Bowen and Guanio (Bowen & Guanio, 2023) have recently (July 2023) reported that in a review of the 30 global systematically important banks[22]' 57% have explicitly excluded nuclear energy from their green or sustainable financing initiatives, while 40% are silent. What view these institutions would take on nuclear fusion energy is unknown.

Banks, including 'green banks' need to balance the risk of the entity to which they are lending not being able to repay the loan against the interest rate charged. As stated above small-scale fusion is an untested technology. The technological challenges that need to be overcome are outlines briefly in Chapter 2 and if these are not overcome any investment is likely to be lost. Therefore, any investment in fusion SMRs will attract high interest rates, making it more likely that a developer will seek equity investment. This coupled with the cost profile (high costs initially) and the extended times (circa 60 years) over which income to repay the funding will be received, means that the cost of capital will be a high proportion of the total costs.

The interaction between the level of risk and the rate of return that an investor would require to offset this risk coupled with the cost profile of a compact fusion reactor mean that the proposition may not be attractive to commercial investors.

Generally, an investor considering investing in a novel technology, such as nuclear fusion, would require a higher rate of return than they would require to invest in a proven technology. The increased return being required to compensate for the possibility that the technology does not live up to expectations, or work at all.

The smaller size of the investment for a small modular reactor when compared to a large reactor means that an investor with a large portfolio may be more willing to invest in a fusion SMR as part of a diversified investment portfolio.

Alhamdan and colleagues (Alhamdan et al., 2023) have elicited the views of a range of stakeholders in the fusion energy economy. Drawing on the insights gained they propose a megafund securitization approach to the financing of fusion. In this approach would enable an investor to, rather than invest in one company

[22] As defined by the Financial Stability Board in November 2021.

and technology, to de-risk their investment by investing in the entire sector, including ancillary technologies.

If funding from commercial sources was not to be available funding would need to be provided by other sources such as Governments[23] whether directly or indirectly.

Funding provided by government.

In the current economic circumstances, the UK Government is still able to borrow money at historically low rates. In May 2023 the Government was able to borrow at a rate of 3.96% compared with an average rate of 7.8% in the period 1980 to 2010 (OECD). This means that the cost of capital for a project funded by the Government would be significantly lower than that of one reliant on commercial investment.

To some extent, Government funding has already occurred. Tokamak Energy have received funding from the UK Government under the Advanced Modular Reactor programme (BEIS, 2018). Similarly, General Fusion has received funding from the Canadian Government (GeekWire, 2018)

If a government were to procure a compact fusion reactor power plant, it would have options as to how the plant would be operated. Prior to the partial privatization in 1990 all the UK's fission power stations were built for and operated by the Government owned entities such as, the Central Electricity Generation Board or the South of Scotland Electricity Board. A similar model could be applied to a fusion fleet. Alternatively, as suggested by the International Project Finance Association (IPFA, 2019) for fission new build, a Government could procure the power plant, paying as costs arise and then sell the plant to the private sector once operational. The advantage of this approach, to the private sector, is that the Government has taken on the risk of the costs escalating or the performance not being what was expected. Therefore, the commercial operator will be able to access capital without having to pay a risk premium, i.e., the additional return that an investor requires to invest in a risky asset rather than a risk free asset.

A variation to this approach would be for the Government to retain ownership of the power plant and to invite bids from private sector organizations to operate the plant for a period of time in a 'Government Owned Contractor Operated'

[23] Which may include several Governments in a supranational organization.

arrangement in return for the income from the sale of the energy. Again, the Government taking on the risks associated with construction will lower the cost of capital.

Alternatively, a government could provide support to private sector developers through providing capital at a rate lower than that at which the private sector developer would be able to obtain from commercial sources. The Government would take on the risk of the loan not being repaid. This support may be regarded as State Aid. State Aid is generally[24] not permitted in the European Union. However, in its Judgment the European Court of Justice (Grand Chamber, 2020) ruled that state aid was allowed for the Hinkley Point C project. World Trade Organization rules, however, do not generally prohibit such aid. Thus, it is likely that state aid would be allowed for a fusion power plant.

A government could also take on the risk by providing a guarantee for loans taken on by a private developer, agreeing to repay the loan if the developer is unable to do so. Thus, the provider of the loan would be relieved of the risk of default and would not charge the developer a risk premium.

Several politicians and political parties, as a response to increasing awareness amongst the electorate of climate change issues, have advocated 'Green New Deals'. Some of these proposals e.g., that of Joe Biden (Biden, 2020) include support for nuclear power. This aspiration has been translated into funding following the election of President Biden (U.S. Department of Energy, 2022).

If a government were to fund the development of a fusion SMR the Government would fund such an investment form the sale of bonds[25], it would be, in practice, acting as an intermediary between the holders of the bonds and the developer. As a government bond is regarded as being risk free the originator of the loan will not require a risk premium.

[24] Exemptions to this prohibition are allowed, inter-alia to support policy aims such as environmental protection and to support research, development and innovation.
[25] Theoretically the Government could fund the investment from revenue, however, very few Governments currently run a budget surplus.

Funds provided by the consumer.
An alternative approach would be to transfer the risk or risk premium to the end consumer. This approach has been used or considered for use in the context of fission power plants.

A contract for a different approach has been used for the Hinkley Point C power plant in the UK. In this approach the developer has been guaranteed a 'strike price [26]for the electricity generated for 35 years. If the wholesale price is less than this strike price the developer will receive top-up payments which are ultimately recovered from the end consumer of the electricity. In the event that the wholesale market price of the electricity is greater than the strike price, the developer will pay the difference to the counterparty[27] Thus, the risk of low wholesale prices has been transferred from the developer. However, under this model the risk associated with cost escalations remains with the developer.
The UK Nuclear Energy (Finance) Act 2022 (H. M. Government) allows the Secretary of State to designate companies who are developing a “nuclear energy generation project” to be funded using a Regulated Asset Base (RAB) model. This approach is described Ross (Ross, 2019) as a mechanism by which investment in an infrastructure project is guaranteed by allowing the developer to pass the cost of the asset to the end consumer as part of their bill. The definition of a “nuclear energy generation project” in the Act does not explicitly specify whether or not this means nuclear fission or whether a fusion project would be eligible for such designation. However, the UK government has indicated in its response to the consultation on the regulation of fusion (BEIS, 2022) that it intends to amend the Nuclear Installations Act to make it clear that a fusion power plant would not require a nuclear site licence.
Questions have, however, been raised as to whether the RAB model is appropriate for nuclear power. Cuthbert (Cuthbert, 2023) believes that, in the context of large scale fission power plants that the long construction times mean that it is unlikely that there will be a sufficient cost advantage in using a RAB model.

[26] Which will increase in-line with inflation.
[27] In this case the counterparty is the Low Carbon Contracts Company which is a company wholly owned by the Secretary of State for Energy Security and Net Zero.

Newbery and colleagues (Newbery et al., 2019) have proposed a hybrid RAB model, similar to that used for the Thames Tideway Project, for fission nuclear generation projects in the UK. In this model, there is sharing of cost overruns between the developer and the Government/consumers, thus spreading the risk of cost overruns to include the developer as well as the consumer. This, the authors believe, will encourage the participation of infrastructure investment funds. This coupled with a 'book building' exercise will further reduce the cost of capital.

When the consumers of the energy are industrial consumers or utilities financial models such as the Finnish Mankala approach may be appropriate. In this approach users of the output form a company to fund the construction and receive the output at cost price in proportion to their investment (Puikkonen, 2010). Lindroos and colleagues (Lindroos et al., 2019) report that Teollisuuden Voima Ltd which owns two fission power plants and is commissioning a third, obtained capital at an interest rate of less than 2.5% in 2016/2017 through this model. Similarly Anglesey Aluminium had a long term contract for the supply of electricity from the Wylfa fission power station covering the years 2000 to 2009 (Anglesey Aluminium Metal Ltd, 2004).

As well as the RAB model, Dieter Helm has suggested a capacity market model (Helm, 2018) in which a nuclear plant developer could bid in an auction to provide capacity, as opposed to power, in a future period prior to the start of construction. If the developer were successful in the auction, it would have a guarantee of income once constructed (the developer would, however, be left with the risk of having to provide the capacity from other sources if the development was unsuccessful or delayed).
In whatever way a compact fusion reactor is funded those providing the funding will require a return (or at least a reasonable prospect of a return) on their investment. This return will be financial in the case of commercial investors. Governments may be willing to receive their return, at least in part, in the form of wider benefits such as increased energy security or reduction of the emissions of greenhouse gasses.

Sources of income

Income from sale of electricity

The UK is committed to net zero CO_2 emissions by 2050 (Parliament, 2019) This will mean the use of unabated fossil fuels for the generation of electricity (i.e. when not coupled with carbon capture and storage (CCS) facilities)[28] will no longer take place and low carbon methods of generation will be required. Some of this need will be met by renewable technologies such as wind and solar. Wind and solar energy suffer from the issue of interruptability. Currently this can be compensated for by the use of flexible gas or other fossil fuel generation, this will not be feasible in a net zero world. In the UK the Committee on Climate Change (Committee on Climate, 2019) has, in its further ambition scenario, estimated that there will be a need for 38% of the nation's electricity to be generated by 'firm' (i.e., always available) low carbon means by 2050.The CCC also project that the UK's demand for electricity will approximately double (from 300 TWh in 2007 to 594 TWh) if the goal of net zero is to be met by 2050.

Income from other uses of the energy

Small-scale fusion is still a number of years away. Other low carbon techniques (including nuclear fission) are available, these technologies may mean that there will be no opportunity for small-scale fusion to contribute to the decarbonization of electricity generation. However, proponents of small-scale fusion believe that there will be a contribution to be made. However, electricity generation is only part of a modern economy's energy needs. In the UK electricity was 17% of total energy use in 2018 (BEIS, 2019).Other uses of the energy produced from a small-scale fusion reactor are described elsewhere in this thesis. For some of these applications the nature of fusion power plants gives them advantages when compared to alternatives. These may provide more lucrative opportunities for small-scale fusion operators.

Conclusions

The novel nature of fusion, being an as yet unproven technology, combined with the cost and income profiles mean that traditional methods of project finance may not be available to potential operators of compact fusion reactors. However, as outlined above a range of alternative funding models are potentially available.

[28] The issue of carbon capture and storage is considered further in Chapter 5 of this thesis.

Some of these, however, will require the involvement of Governments for them to be available.

Whatever method a potential developer of a fusion SMR uses to raise the necessary finances they (and those providing the finance) will need to ascertain whether they will obtain a return or sufficiently large return on the capital. One method of assessing this is to consider the expected Net Present Value (NPV). This is considered in Chapter 4.

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Chapter 4: Calculations of net present value for a small modular fusion power plant under a range of scenarios

The work presented in this Chapter is based on Webbe-Wood, D., & Nuttall, W. J. (2023). Calculations of net present value for a small modular fusion power plant under a range of scenarios. *Proceedings of the Institution of Civil Engineers - Energy*, 1-24. https://doi.org/10.1680/jener.21.00103. The construction and use of the models described was carried out by myself and I produced the first draft of the paper. Subsequent drafts of the paper have benefited from comments from Professor Nuttall. It has also benfited from comments from the anonymous referees.

Introduction

As discussed in Chapter 3 there are a range of sources from which a developer of a fusion SMR may obtain finance. Whatever the source of the funding the investor would wish to have confidence that are likely to receive a return on their investment. This chapter makes use of one technique, the calculation of NPVs to investigate this question.

Nuclear power currently produces approximately 10 percent of the world's electricity (BP, 2019) and further use has been proposed as part of the necessary reduction in the use of fossil fuels in the global energy mix, thereby enabling targets for atmospheric concentrations of global warming gases to be met. The IEA (IEA, 2022) project that for net zero emissions to be achieved by 2050 nuclear capacity will need to almost double from 413 GW in 2022 to 812 GW. To date, the use of nuclear power for energy purposes has been limited to the use of fission. Similarly, all the commercial nuclear power projects currently under construction, or planned, are fission based.

Nuclear fission, however, has drawbacks which add cost and may limit its acceptability to the public. These relate to radioactive waste production, including actinide bearing wastes requiring safe disposal and the potential for large-scale accidents that have significant consequences off-site. Fusion does not have these drawbacks to any significant extent (Logan et al., 1990). However, the development of nuclear fusion for the generation of electricity has been a protracted process. Current international plans as represented by the ITER, research and testing, reactor under construction and the planned DEMO follow-on power plant are not envisaged to produce power until the middle of the century. Current fission generation projects are capital intensive and require long construction times, for example, the Hinkley Point C project in the United Kingdom is projected to cost £25 to £26 billion and not generate electricity until 2027 (World Nuclear News, 2022), construction having commenced in 2017. One proposed solution to these issues is the construction of Small Modular Reactors (SMRs). These, proponents argue, have the advantages *inter alia* that they allow construction to be undertaken in factory conditions thus improving productivity. Learning effects between the manufacture of successive modules will lower costs and construction times and, in turn, the reduced cost of the modules will decrease the capital requirements[29]. Whilst many of these programmes for SMRs such as that of the United Kingdom Government (BEIS, 2018) are predominately focused on the use of fission reactors (of various designs), the attractions of the small modular approach are potentially of equal applicability to fusion reactors. It is noteworthy that the fusion start-up Tokomak Energy received UK AMR competition funding in 2018. Proponents believe that it is possible to build fusion reactors which are smaller, quicker and cheaper (Gryaznevich et al., 2015). Numerous groups worldwide are developing SMR fusion concepts intended to generate electricity for sale to the grid. Readers interested in the scientific and engineering principles behind plans to commercialise fusion are referred to Nuttall et al. (Nuttall et al., 2020). The book also gives details of many of the companies involved in such commercialisation efforts.

Whether or not these plans reach fruition, the question remains as to whether fusion based electricity generation projects will represent an attractive proposition to an investor. This paper attempts to provide some partial answers to this question. Whilst the nature of some of the designs for fusion SMRs under consideration have the potential to produce energy/heat suitable for use for applications other than the generation of electricity, the scenario considered here is of an operator generating electricity for delivery to the UK grid in 2040. Calculations were also carried out to investigate the sensitivity of the NPV results to these parameters.

Small Modular Reactor (SMR) Concept

Annex IV of the 2007 IAEA Nuclear Technology Review (IAEA, 2007) defines a small nuclear power plant as one that has an equivalent electrical power output of less than 300 MW. The World Nuclear Association defines a modular reactor as

[29] As no fission SMRs have been built, the learning effect is postulated and not proven.

one *"designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times"* (World Nuclear Association, 2016). Rolls Royce have proposed a fission design with modules having an output of 470 MW(e) (Rolls Royce, 2022), which is receiving funding under the United Kingdom Advance Nuclear Technologies programme (BEIS, 2018) In this instance, the term "small" is held to refer to the ability for component modules to be transported to site by road. This definition differs from that of others, for example the Nuclear Energy Agency (Nuclear Energy Agency, 2021) use a definition of a small reactor as being one with an output less than 300 $MW_{(e)}$.

Small, modular *fission* reactors have a number of possible advantages. In 2010, the then US Secretary of Energy stated.

> *"Their small size makes them suitable to small electric grids so they are a good option for locations that cannot accommodate large-scale plants. The modular construction process would make them more affordable by reducing capital costs and construction times. Their size would also increase flexibility for utilities since they could add units as demand changes, or use them for on-site replacement of aging fossil fuel plants."*
> (Chu, 2010)

A review of the research literature regarding the economic and financial aspects of fission SMRs, including identification of the gaps in the literature, has been carried out by Mignacca and Locatelli (Mignacca & Locatelli, 2020). Whilst this work was targeted at fission SMRs, much of the work identified can also be applied to considerations of fusion SMRs, however, the gaps identified by Mignacca and Locatelli will largely remain.

The Concept of Net Present Value (NPV)

The concept of NPV is intended to allow expenditures and incomes occurring at different times to be compared. To do this, incomes and expenditures are discounted with respect to time so that income and expenditure streams occurring in the distant future carry less weight than those received in the nearer future. The NPV is given by the equation:

$$NPV = \sum_{t=1}^{n} \frac{c_t}{(1+r)^t}$$

Where c_t is the cash flow (either positive or negative) in period t

t is the time period in which the cash flow occurs,

r is the discount rate and,

n the number of time periods

Thus, the project's total NPV is the sum of the discounted cash flows in each time period through to the end of the project. The calculated NPV is sensitive to the discount rate used which reflects the time value of money i.e., that reduced value placed on incomes and expenditures in the distant future compared to those occurring at a closer time. It also reflects the cost of capital to the developer and the risk of the project not succeeding.

Alternative methods of obtaining the necessary finance for a fusion SMR project are available. These include the provision of government subsidies, outright purchase government, using a Special Purpose Vehicle to keep expenditure off the balance sheet of the developer and the use of the Regulated Asset Base approach. These and other approaches are discussed in Chapter 3 of this this thesis.

Net Present Value Calculations

The NPV is the discounted income minus the discounted expenditures. In this case the income is derived from the sale of electricity and the expenditures are capital expenditure and the ongoing operational costs.

It is usual in techno-economic studies of this type to work with “real” rather than “nominal” costs and revenues. The benefit of the approach is to remove the logical complications arising from inflation. Nominal prices are those actually charged, real prices are the equivalent concepts presented independent of inflation. Inflation is a macroeconomic property of the economy independent of the merits, or otherwise, of technological concerns. The conversion from real to nominal values is, in principle, a relatively simple adjustment if the applicable inflation rate is known. Real costs values are usually expressed as those applicable at a fixed point in time, usually expressed with a reference year. In this chapter the decision has been made to reference financial values to the year 2018. This year has been chosen because it remains relatively recent, but it predates two distortionary global crises. The first crisis was the COVID-19 pandemic and the second is the war in Ukraine and its associated economic fall-out. Inflation is now rising fast around the world and if the values were to referenced to 2022 there would be much uncertainty (in the relationship between real and nominal values) as a consequence of prices and costs changing at a fast pace throughout the year. The global economic landscape was much more stable in 2018 and for that reason this has been chosen as a pragmatic choice which introduces few additional uncertainties.

Price of electricity

The income received from the generation of electricity, and hence the NPV of a fusion SMR power plant, is dependent on the price received for the electricity. To take account of this, five scenarios were considered:

- The operator obtains a price for electricity at the strike price that has been agreed for the Hinkley Point C power plant. This is £102.73 per MWh at June 2018 prices (National Audit Office, 2017). The original agreement specified a price of £92.50 in 2012 prices, reducing to £89.50 if a decision was taken to proceed with the Sizewell C project.
- A price is obtained equal to the strike price that it is believed was being sought by the developers of the formerly proposed Wylfa Newydd power plant. This has been taken to be £86 per MWh at June 2018 prices (The Financial Times, 2018).
- Three scenarios based on the assumptions in Annex M of the BEIS 2019 energy and emissions projections (BEIS, 2020). This contains three projections, one reference price projection, one high price projection and one low price projection. These projections however, end in 2040, long before the expected end of life of a fusion power plant commencing operation in 2040, as considered here. Projections for electricity prices have been produced by the European Union (European Commission, 2018). These projections suggest that there will be little increase in the price of electricity between 2040 and 2070. Therefore, the 2040 values from the BEIS projection are used. These prices are given in table 3.1 below:

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Table 4.1: BEIS Electricity Price Scenarios

Electricity Price Scenario	Price (£ per MWhr (2018 £))
BEIS High	68
BEIS Reference	63
BEIS Low	55

In this chapter, these electricity prices are referred to as Hinkley, Wylfa, BEIS High, BEIS Reference and BEIS Low, respectively.

Similarly, the choice of discount rate used has a major impact on the calculated NPV. Again, a number of values were considered:

- A rate of 9%. This is the implicit rate of return that investors in the Hinkley Point C project will receive (National Audit Office, 2017)
- A rate of 6.66% which corresponds to the situation where private investors are responsible for 2/3 of the capital cost (and receive the same rate of return as Hinkley Point C investors) and the Government funds 1/3 through the issue of bonds at 2%.
- A rate of 3.5 % which is the rate recommended by HM Treasury in the guidance for appraisal of public sector projects (H. M. Treasury, 2011)
- Finally, a rate of 2% which according to Helm (Helm, 2018), is the rate at which that the Government could have, in 2018 issued bonds to cover the total costs.

This range of discount rate values and prices for the electricity produced means that the NPVs under twenty different scenarios were calculated. The structure of the models is such that adapting them for other discount rates and/or electricity prices would be straightforward.

<u>Costs of construction</u>

Two sources of construction cost data have been in this study. Firstly, Data on the capital and operating costs, construction times and plant availability were obtained from a report prepared for Tokamak Energy by an engineering consultancy as part of Tokamak Energy's submission to the UK Government's Advanced Modular Reactor competition in 2019. That document remains the property of Tokamak Energy.

The report derives a breakdown of the various cost components for a two-module tokamak design producing 175 MW(e) per unit. Information, including underlying assumptions, is provided for both first-of-a-kind and Nth-of-a-kind power plants making use of cost reductions due to learning effects. The cost data has been estimated by using a mix of unit area and volume costs for structures, estimates of raw material costs and manufacturing factors for equipment and engineering judgement. Data is also provided for the expected frequencies of both planned and unplanned shutdowns. The calculation of such cost data does not form part of the work in this thesis. In the case of the consideration of a portfolio of fusion plants in this thesis (Chapter 6), the data has been updated from 2018 £s to 2020 £s using the UK RPI time series (Office for National Statistics, 2023) so as to be on the same basis as the other cost and price data used in those calculations.

These costs are for both a First of a Kind (FOAK) power plant and for an N^{th} of a Kind (NOAK) when the effects of learning have reduced the construction and operating costs and operational experience has improved the availability of the plant. In this case N is taken to be the 20^{th} plant (i.e., the 39^{th} and 40^{th} modules). These plants will have been deployed at a rate of a 2-module power plant once every two years. Thus, the NOAK plant would not, on this basis, commence generation until 2060.

The design concept consists of two Tokamak fusion reactor modules each supplying an electrical output of 175 MW to the grid. This output is reduced in the model by the need to provide a "hotel load" for the operation of the power plant and by outages. In the baseline FOAK case the first module is modelled as being constructed over a period of four years with the costs being incurred as equal amounts in each year, with the exception of the costs associated with licensing and the purchase and preparation of the site which are assumed to occur in the first year. The generation of electricity commences in the fifth year. The second module commences construction one year after the first module and hence commences generation one year later than the first module.

Decommissioning costs for both modules are accounted for at the start of construction of the first module. As there is little experience of the decommissioning of fusion plants, any decommissioning costs estimate must be subject to large uncertainties. However, fusion plants will not face the costs and other issues associated with the disposal of spent fission fuels. There are potential issues, however, with the disposal of steel components as a result of neutron activation. As discussed by Bailey and colleagues (Bailey et al., 2021) it is possible that such material will need to be disposed of as Intermediate Level Waste with the attendant costs. Efforts are underway to develop reduced activation materials such as the EUROFER reduced activation steel (Van der Schaaf et al., 2003)

As well as the cost of construction the calculations of NPVs take account of consumable items, staff costs and the cost of maintenance operations. Tritium for the first load is treated as part of the construction costs. As noted by Pearson and colleagues (Pearson et al., 2017) supplies of tritium for start-up of a fusion reactor are not assured and hence, may be more expensive than assumed here.

Site purchase, land preparation costs and licensing costs for both modules are modelled as being incurred in the first year of construction a similar approach has been used by Black and colleagues (Black & Peterson, 2019) in their economic assessment of fission SMRs.

Planned shutdowns of the fusion reactor, and hence loss of income, are assumed to occur at the intervals assumed in the by the developers. Unplanned shutdowns are modelled as occurring randomly with the frequencies (and durations) specified in table 4.2 below.

Table 4.2 First of a Kind and Nth of a Kind Properties

	First of a Kind	Nth of a Kind
Build time of modules	4 years	4 years
Frequency of planned shutdowns	Once every 4 years	Once every 4 years
Duration of planned shutdowns	6 months	5 months
Frequency of unplanned shutdowns	Once every 4 years lasting for 2 months	Once every 5 years lasting for 2 months
Load Factor	98%	99%

For the calculations of the NPV of the NOAK power plant both modules are assumed to be built concurrently over a period of four years. Costs are reduced due to learning over the construction of the fleet of power plants.

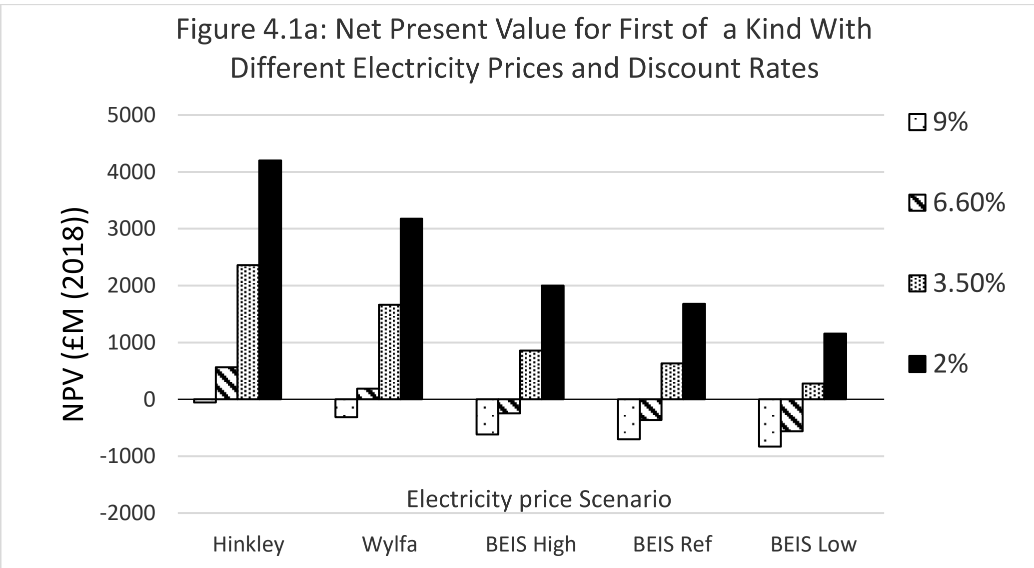
The load factor (the proportion of the notional output actually obtained through deliberate operation at a power less than the design power) is increased. Whilst the frequency of planned outages remains the same their duration and hence the amount of output lost is reduced. Unplanned outages are assumed to have the same duration as in the FOAK case but occur with a reduced frequency.

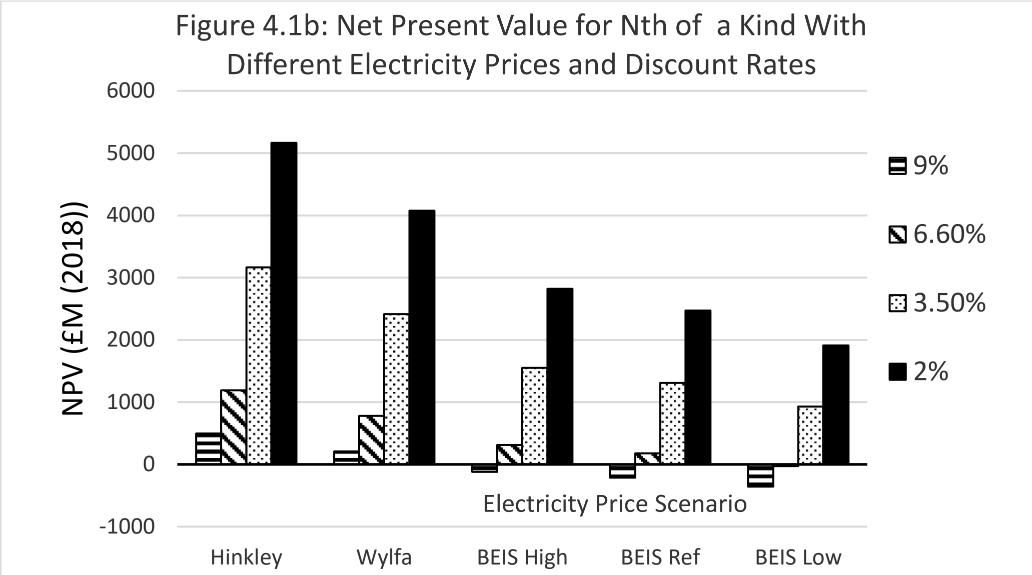
As well as the calculations for this design concept, calculations were carried out for a power plant based upon a study carried out by Bechtel and partners (Bechtel National Inc et al., 2017) to provide cost information for a fusion power plant based on four design concepts. These calculations are used to provide a check with the calculations based on the developer's design. This comparison is discussed further below.

As well as the calculations of NPVs for the various scenarios discussed above calculations were carried out to investigate the relationship between build time and NPV and the impact of unplanned outages occurring more frequently than assumed in the baseline case on the NPV. Calculations were also carried out to explore the relationship between costs and discount rates that would result in a positive NPV being obtained in different electricity price scenarios,

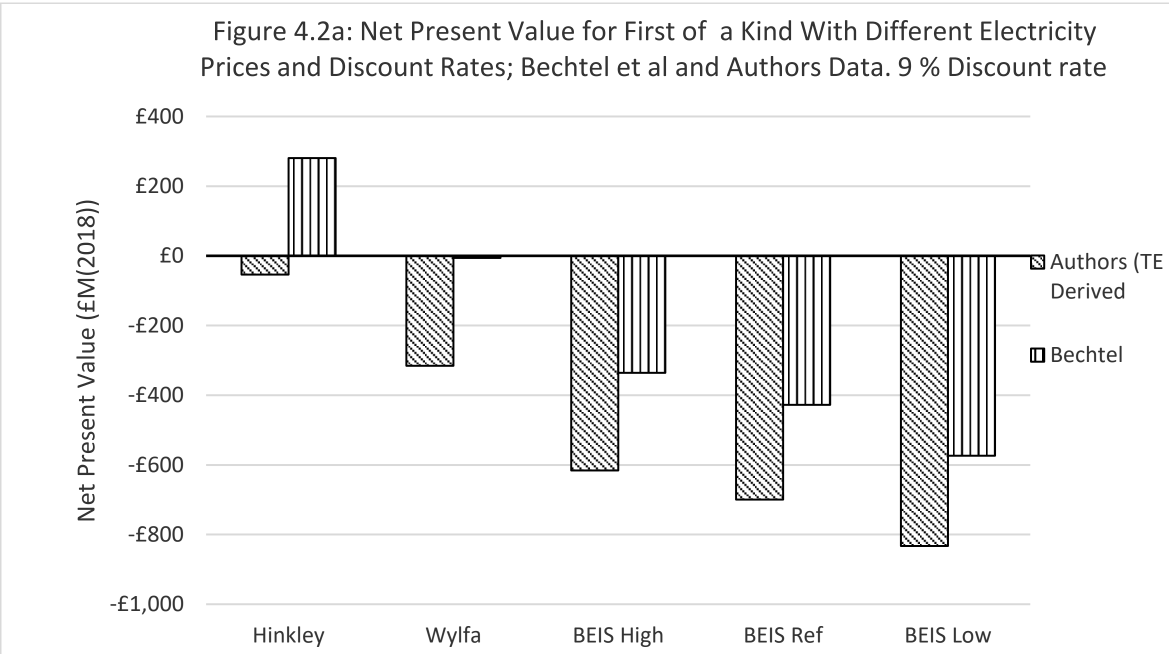
In all of the calculations of NPVs the only source of income is that obtained from the sale of electricity. No account has been taken in these calculations of income from the provision of other publics goods such as carbon credits as it is unknown what form such provisions would have during the lifetime of the plant. This contrasts with the approach taken in subsequent chapters where such income plays part of the business cases.

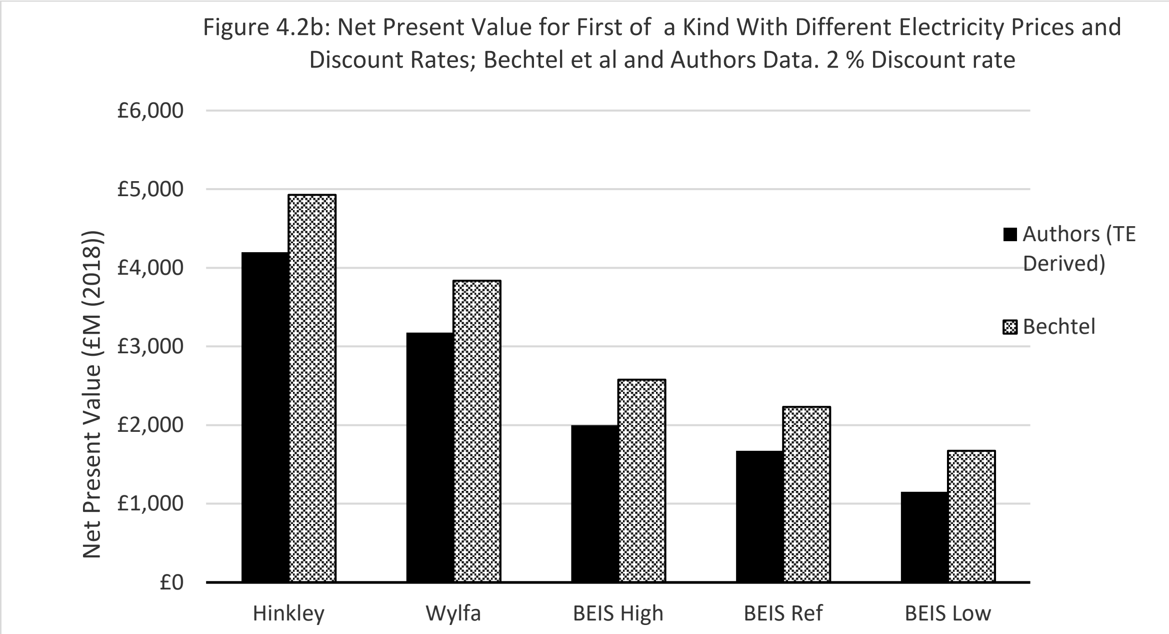
The results of the baseline calculations are summarised in figures 4.1a and b below:





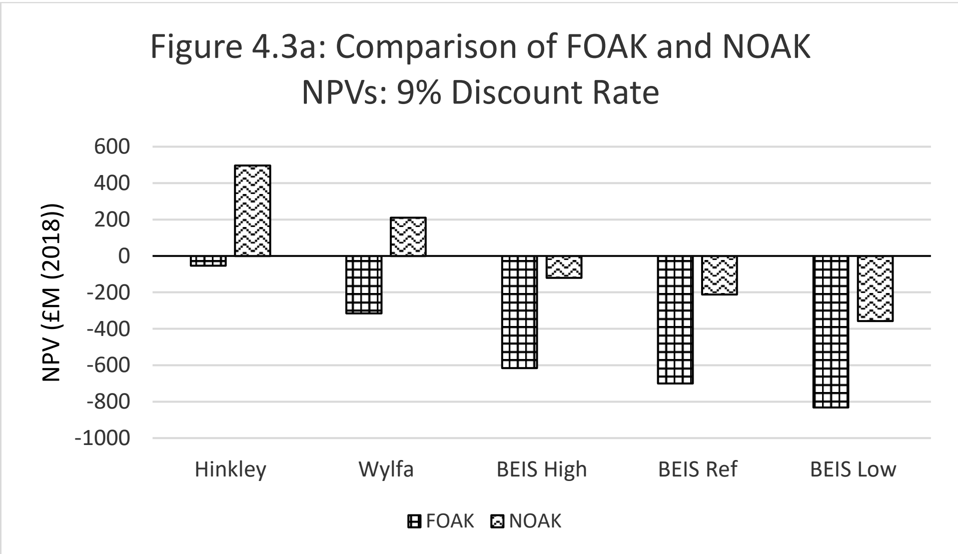
As discussed above, calculations were also carried out making use of the cost data (converted to 2018 costs) derived by the Bechtel led team (Bechtel National Inc et al., 2017) to provide confidence that the estimates of NPV derived using the developer's data were broadly comparable with those obtained from other sources. The results of these comparisons are given in figures 4.2a & 4.2b below:

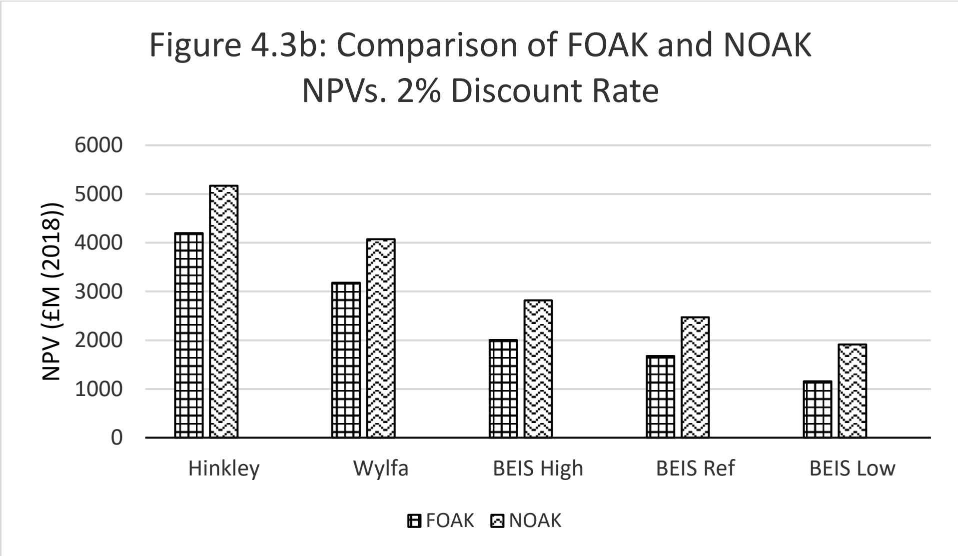




As can be seen the comparison with the cost data from the Bechtel led team show that the cost estimates used in the main for this work are comparable with estimates from other sources.

Figures 4.3a and b give a comparison of the results (with 9% and 2% discount rates) between FOAK and NOAK power plants. Not surprisingly in all circumstances the NOAK examples have the highest (or least negative) NPVs.





Results for the other two discount rates are intermediate to those for the 9% and 2% cases.

These results show that as has been seen repeatedly in nuclear energy economic assessments that the discount rate obtained is, by far, the main determinant of the net present values observed. This is a consequence of nuclear power plants, whether fission or fusion, having the costs predominately in the construction stage, and consequently only discounted by a small amount. Conversely, the income will be received over the lifetime of the plant, with the incomes later in the lifetime being heavily discounted.

Relationship Between Build Time and Net Present Value.

Any change in the time taken to build a fusion SMR will impact on the NPV of the plant. A shorter build time will bring forward the commencement of the start of generation and sale of electricity. Thus, the discounting of this income will be reduced increasing the NPV. This will (in part or fully) be offset by the reduced discounting of the construction costs resulting from the reduced building time. Conversely increasing the build time will increase the discounting of both expenditures and income. In most cases the consequence will be to cause costs to rise in importance relative to revenues.

To investigate this interaction, versions of the models were developed. In the case of the FOAK model the build time was allowed to vary (in two-month intervals) in the range 36 months to 90 months, compared to the baseline build time of 5 years. Whether it is feasible to build the plant in a shortened time is not considered here, the calculations being carried out to investigate the effect of NPV. For the NOAK model the build time was varied between 24 months and 72 months) (with a baseline of 48 months). In both cases the operating costs and incomes were not adjusted. The results of these calculations are illustrated in Figures 4.4a and b below:

Figure 4.4a: Difference in FOAK Net Present Values with Different Construction Times From 60 Month Build Time with Discount Rate of 3.5 %

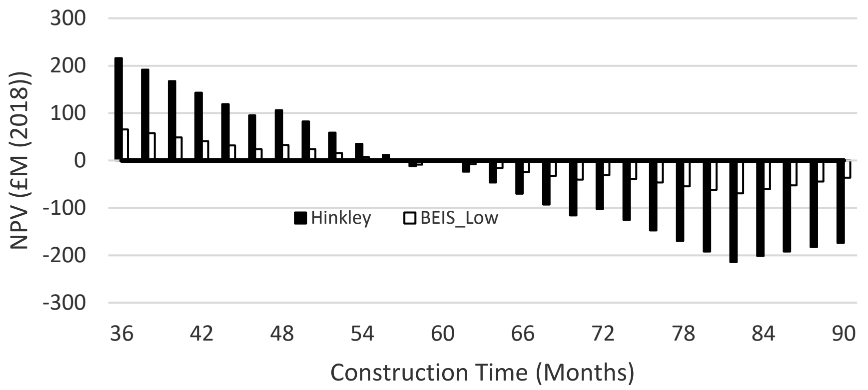
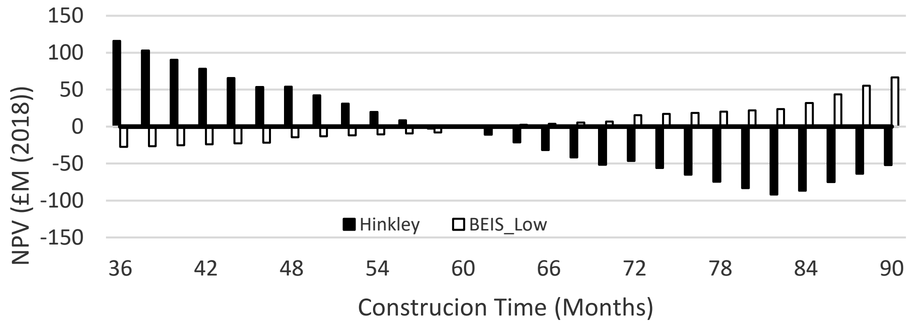


Figure 4.4b: Difference in FOAK Net Present Values with Different Construction Times From 60 Month Build Time with Discount Rate of 9%



The results for other combinations of electricity price and discount rates are intermediate to those shown above.

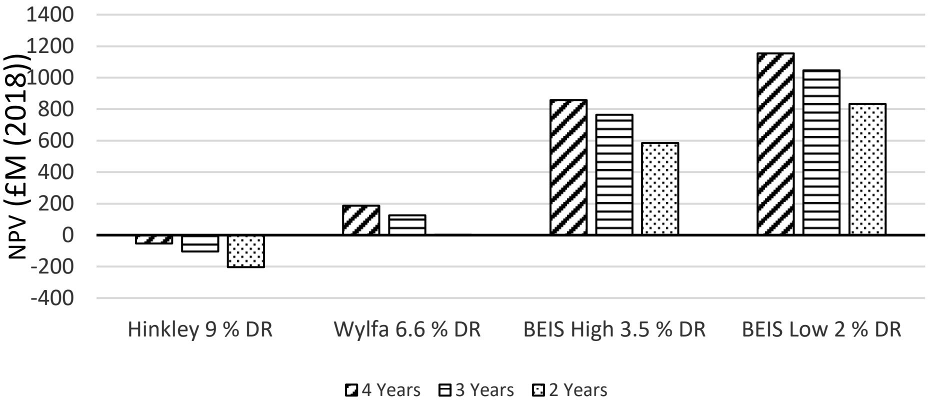
As can be seen from the figures above, there is an interplay between the effects of different discount rates, the price of electricity and changes in the time needed for construction. Changing the time needed for construction does not change the capital cost, the effect on the NPV is a result of consequent changes in the amount of discounting. At high electricity prices and low discount rates, increased discounting of income from the sale of electricity due to the delay in the start of generation results in a reduced NPV. Conversely, a reduction in the construction time reduces the discounting of this income giving an increased NPV. Whilst this effect is present with a low electricity price its size is smaller.

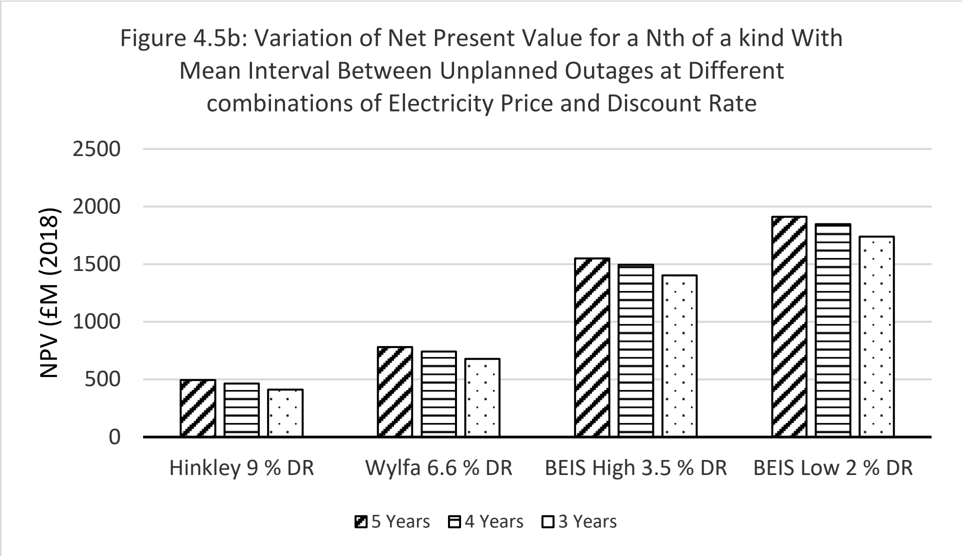
With a low electricity price and a high discount rate the effect of an extended construction time increasing the discounting of the construction costs can outweigh the impact of the increased discounting of the income from the sale of electricity leading to an increase in the NPV. At a high electricity price this effect is not seen.

Effect of More Frequent Unplanned Outages

The income obtained, and hence the NPV, of a fusion power plant will depend on the plants availability to supply electricity to the grid for as much time as is possible. The calculation of NPVs include periods of unavailability due to both planned and unplanned outages. The frequencies and durations of the outages are given in Table 4.1 for the baseline cases. Nuclear fusion, however, will not be a mature technology when the first plants are constructed and operated. It is possible that unplanned outages will occur more frequently than expected by the developers. To investigate the impact of more frequent outages, sensitivity analyses have been carried out. The results of these calculations are presented in graphs 5a and b below. In the case of the FOAK power plant the baseline of one unplanned outage in every four years (on average) is compared to the cases of one such outage every three and one every two years. For the NOAK case the baseline of one outage in every 5 years is compared to one outage every four or three years.

Figure 4.5a: Variation of Net Present Value for a First of a kind With Mean Interval Between Unplanned Outages at Different combinations of Electricity Price and Discount Rate





For clarity figures 4.5a and b only show the results for a selection of the possible combinations of electricity prices and discount rates. The results for the other possible combinations are intermediate to those shown.

As expected, an increase of the frequency of unplanned outages will lead to a reduction in the NPV. This effect, as can be seen, is not large. These calculations only take account of the reduction in income due to the inability to sell electricity during the outage. As Steer and colleagues (Steer et al., 2011) have pointed out the operator is likely to have contractual obligations to supply its customers and will have to purchase electricity from the system operator's reserve or on the open market for supply to the customer. These costs have not been taken into account in the analysis reported here.

If the frequency of unplanned outages is sufficiently high, or their duration is sufficiently long the effect may be such that the NPV becomes negative. The ability to minimise the impact of unplanned outages on generation of electricity will be central to the economic viability of a fusion SMR.

Combination of Capital Cost and Discount Rates Giving Acceptable NPVs

There are a range of possible combinations of construction costs, electricity price and discount rates that result in positive NPVs.

To investigate these combinations, calculations were carried out in which the price of electricity, the capital costs and discount rates are allowed to vary randomly (within specified limits) with no correlation between these parameter values. The NPVs for each of the combinations were calculated.

These calculations were performed using the SiPmath add-in for Excel (Savage et al., 2017). Those combinations where the desired NPV criteria were met were retained. These results were further filtered to identify those combinations where the NPV values just meet the criteria. These values are then plotted to provide a visualisation of the surface where combinations of the input parameters give an NPV meeting the criteria. These are shown below. Combinations of the input parameters to the right and above the surface result in a positive NPV. Conversely, values to the left and below result in a negative NPV. These surfaces are shown in figures 4.6 and 4.7 below:

Figure 4.6: Combinations of capital cost, discount rates and electricity price which give NPVs greater than zero, First of a Kind

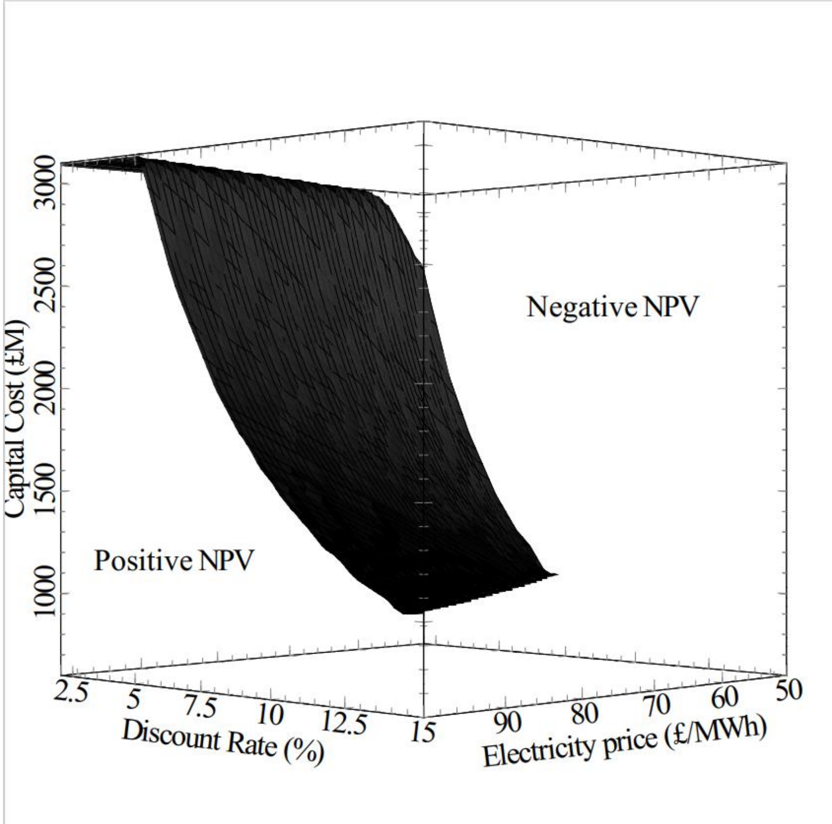
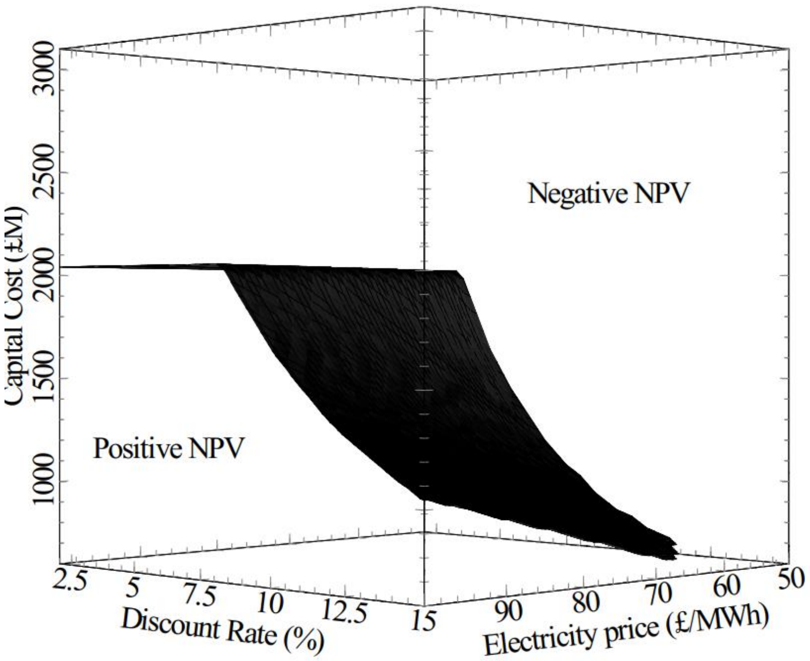


Figure 4.7: Combinations of capital cost, discount rates and electricity price which give NPVs greater than zero for a NOAK plant.



As can be seen there are combinations of the parameters (electricity price, discount rate and plant cost) that result in a “sweet volume” where in which such a reactor would deliver a positive NPV. Unsurprisingly this volume is in the region where plant costs and discount rates are high and discount rates are high.

Chapter Conclusions

Proponents of the construction of fusion SMR power plants for the generation of electricity believe that they will be able to overcome the scientific and engineering challenges that remain before their goal is achieved. However, overcoming these challenges does not necessarily mean that such power plants will represent an attractive proposition to an investor.

Calculations have been carried out to assess the NPV of these power plants in different discount rate and electricity prices scenarios. The effects of changes in the construction time and frequency of unplanned outages on the NPV have been investigated. Calculations have also been carried out to investigate the combinations of construction costs, discount rates and electricity prices that result in criteria for the return on investment being met.

These calculations show that are combinations of electricity price, capital costs and discount rates which constitute a “sweet spot” in which a fusion SMR power

plant would be financially viable without the need for subsidy or other forms of support such as carbon credits.
In this chapter three dimensions of uncertainty for those contemplating the construction of a new small modular fusion power plant have been considered. These dimensions are:

- The capital cost of construction,
- The economic discount rate (essentially equivalent for project finance to the Weighted Average Cost of Capital (WACC[30])), and
- The electricity price (which for simplicity, once set, are regarded as stable for the whole project lifetime).

The range of values considered for each of these three key parameters has been set symmetrically within its own likely range and more importantly with an equivalent attitude to risk to that used in the other two cases. That is a capital cost of £1 Bn is roughly as probable as a capital cost as a cost of £3 Bn and this range of likelihood is the same as that seen when a range of electricity prices between £50/MWh and £100/MWh is posited. From the data and the analysis presented it is observed that, as might reasonably have been expected, there are monotonic trends favouring a positive NPV arising from higher electricity prices and lower discount rates. The analysis also shows that the role of capital cost is somewhat different. There are levels of capital cost (£2Bn in the case of a NOAK project) above which a positive NPV is simply not possible. This points to a requirement, and as noted by Mignacca and Locatelli (Mignacca & Locatelli, 2020) the equivalent issue effects the developers of fission SMRs that the capital costs of construction are the key strategic concern with the potential to derail the whole enterprise. It is a key conclusion of this chapter that capital cost minimisation must be a key goal for technologists seeking to develop a small modular fusion power plant as a commercial proposition.

Looking to the future there are two ways in which the work presented in this chapter might be improved. First, once set, a fixed electricity price is deployed for the project duration. This is mimicking a feed-in-tariff or some other long-term contract, but greater realism could be achieved with a more sophisticated

[30] The WACC combines the cost of equity and the cost of debt. The cost of equity will incorporate the risk premium that the investors require.

treatment of electricity prices. Second for project developers the key uncertainties are likely to resolve themselves at different points during the project lifetime. For example, the discount rate, or WACC, is likely to be established before construction starts. The capital cost of construction is likely to be known as construction completes, but the average electricity price is not likely to be known until the plant is shutdown awaiting decommissioning. There is also the potential to make use of methods associated with the value of flexibility such as those outlined by Cardin and colleagues (Cardin et al., 2017) to introduce time varying information.

As noted in Chapters 1 and 3, the generation of electricity for sale to the grid is not the only "product" that a fusion SMR can be used to produce. Also, there is the potential for the developer and operator to make use of engineering flexibilities / real options and a portfolio approach to increase the expected NPV. These are considered in Chapters 5 and 6.

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Chapter 5: The Options Value of Blue Hydrogen in a Low Carbon Energy System.

The work in this Chapter is based upon Webbe-Wood, D., Nuttall, W. J., Kazantzis, N. K., & Chyong, C. K. (2023). The Option Value of Blue Hydrogen in a Low Carbon System. Cambridge Energy Policy Research Group Working Paper 2309. The original methodology of Dr Chyong (Banking Environment Initiative, 2012) has been extended by myself to cover the scenarios described here. The modelling and the first draft of the working paper were carried out by myself. Some text has been provided by Professor Kazantzis. Professors Nuttall and Kazantzis and Dr Chyong have supplied comments on the text and suggestions on the methodology used. Comments have also been supplied by the anonymous referee(s).

Introduction

This Chapter of the thesis diverts from the consideration of a fusion SMR. In this chapter the example of the production of blue hydrogen from methane to explore the concepts of engineering flexibilities and real options which were introduced in Chapter 1. It will lead to the application of these concepts, in conjunction with portfolio theory, to the case of a fleet of fusion SMRs. This will be discussed in Chapter 6.

Background

In this chapter the methodology developed by Chyong and colleagues (BEI, 2012) has been extended and enhanced. Chyong and colleagues made use of a real options approach to consider the case of a gas fired power constructed so as to be retrofitted with a Carbon Capture and Storage unit[31]. This approach has been adapted to the case of a plant producing "blue" hydrogen from natural gas (predominately methane) by using the methane steam reforming (MSR) process.

Hydrogen is forecast by e.g. the International Energy Agency (IEA) (IEA, 2019) to play a key role in a clean, secure and affordable energy future. The IEA estimates that (IEA, 2021) 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. The Hydrogen Council and McKinsey (Hydrogen Council, 2020) forecast a demand of 660 Mt by 2050.

[31] Chyong and colleagues also considered two other cases, but these are not relevant to this thesis.

Numerous methods are available for the production of hydrogen via a range of energy sources. Hydrogen produced by different methods and sources are often referred to as being of different “colours”. A taxonomy of different hydrogen colours has been created to describe these e.g. (H2 Bulletin, 2021). Current methods of production are (IEA, 2021) 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%). Schemes have been proposed to utilise hydrogen in place of natural gas (predominantly methane) for domestic supplies such as the plan to commence blending 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 (produced from fossil fuels with CCS) and 40% from fossil fuel sources without the use of Carbon Capture and Storage (CCS) (grey hydrogen). The UK Government’s hydrogen strategy (H.M. 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 (hydrogen produced by electrolysis of water using a sustainable means of generating the electricity), 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).

The operator of a Methane Steam Reformation (MSR) plant has the option of fitting a Carbon Capture and Storage (CCS) unit during construction and operating this unit throughout the lifetime of the plant, or alternatively, not to fit the CCS unit. The fitting of the CCS unit brings with it extra costs, both capital and operational. 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" (Banking Environment Initiative, 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 on the basis of 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, calculations have been carried out in a stochastic manner using Monte-Carlo simulation techniques to explicitly account for these uncertainties and derive NPV probability distribution profiles that can be statistically characterised. This availability of statistics relating to the NPV allows more informed decisions to be made than would be the case with a single point estimate of the value. A developer would not, however, be able to account for the effects of possible changes in the construction of the plant (i.e., retrofit CCS) or change to the operations (ceasing the operation of the CCS unit) to reflect changes in the "worlds[32]" in which the MSR plant would be operating. A schematic flow chart of the decision-making process involved is given in Fig 5.1 and is discussed below.

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 their access to upside opportunities) or to minimise the effect of changes that could reduce the NPV (i.e., limit their exposure to downside risk) in an inherently uncertain system operating 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).

Methodological Framework

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 in the way in which the plant is operated. This potential flexibility gives the operator the ability to respond to opportunities that may arise, as well as to manage potential downside risks as a

[32] The term “worlds” is used in this thesis to describe possible future energy and carbon emission price scenarios.

result of external changes and thereby increase 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 to the engineering project making use of techniques analogous to those used for the valuation of 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 and Scholtes (de Neufville & Scholtes, 2011).

Cardin (Cardin, 2013) has proposed a structure for procedures to enable flexibility in the design and operation of engineering systems that will operate in circumstances of uncertainly. This structure consists of a number of 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 MSR plant is constructed to produce hydrogen using methane as both the feedstock and energy source for the process and CO_2 is released to the atmosphere. In the second scenario, the MSR plant is constructed with a CCS unit, to reduce the release of CO_2 to the atmosphere, from the start. For both of these 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 that will be used in sequel to inform economic performance assessment and the decision-making as to which configuration to proceed with.

Stage 2 – Uncertainty Recognition

The environment in which the plant (whichever variant) will operate will be subject to a number of uncertainties inevitably impacting on 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. Monte-Carlo simulation techniques could therefore be employed to overcome the aforementioned limitations, as well as to mathematically address the "flaw of averages" associated with potentially asymmetric impact on process performance output metrics of otherwise symmetrically distributed uncertain inputs.[33]

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 / natural gas
- The price of permits to release CO_2 to the atmosphere or carbon taxes.
- In the case of the MSR 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

Consideration of these uncertainties leads to two flexible concepts which would enable the operator to take advantage of the resolution of 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, so as 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 lead to various costs being incurred.
- Amendment of the design for the plant fitted with CCS from the initial construction stage such that it is possible to operate the MSR plant without operating the CCS unit[34] with corresponding lower operating

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

[34] This analysis only considers the financial implications, to the operators, of stopping the operation of the CCS unit. Wider political and regulatory factors are not considered in the present study.

costs in operating costs. Ceasing operation of the CCS unit, which had been operated since construction, will increase the costs associated with the release of CO_2 to the atmosphere.

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 of the plant and the necessary additional costs identified. Similarly, the additional costs (and savings) associated with ceasing the operation of the carbon capture unit are identified.

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 a number of factors including the costs of natural gas[35], the price the hydrogen is sold for, capital costs, discount rates, the effect of the operation of the CCS on the amount of hydrogen available for sale. Such costs are typically not well known in advance and therefore, any probability distribution for these parameters will have a high degree of variance.

Valuation of the Engineering Flexibility

The value of the right to exercise the option, to 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 a practical and potentially insightful 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 the determination/quantification of the risk-adjusted discount rate, or the risk-adjusted probabilities are removed. Also, the construction of a replicating portfolio[36] has no physical meaning in

[35] 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.

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

engineering real options as the underlying assets (net cash flows) are not traded on the market (de Neufville & Scholtes, 2011).

II. These methods are not able simultaneously to 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 gives rise to additional 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 comparison of 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 derivation of parameters such as the standard deviation of the NPV, Capex, Value at Risk (VaR) for a given probability level (5^{th} percentile of the cumulative distribution) capturing the potential for downside risk, the complementary Value at Gain (VaG) (95^{th} percentile of the distribution) capturing the potential for upside opportunities. This enables the establishment of a link to the risk profile of the decision maker. The above represent key comparative advantages over financial real options analysis within which a single value of the option is generated or a traditional optimisation framework relying on a single objective function.

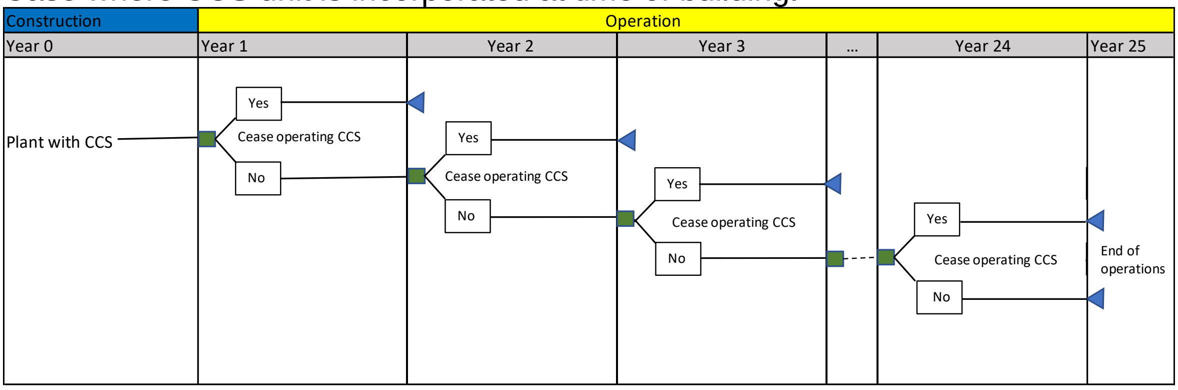
Within the above context, for the scenarios where the flexibilities are available to the operator, calculations can also be carried out to evaluate the distribution of the NPVs.

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 results in a range of possible configuration pathways through the lifetime of the plant. Two sets of pathways are considered (one for the case where the plant is constructed with the CCS unit and the option is to cease operation of the unit and one where the option is to retrofit the CCS unit). Once a sequestration unit has been fitted the option to cease operation of the unit is not considered.

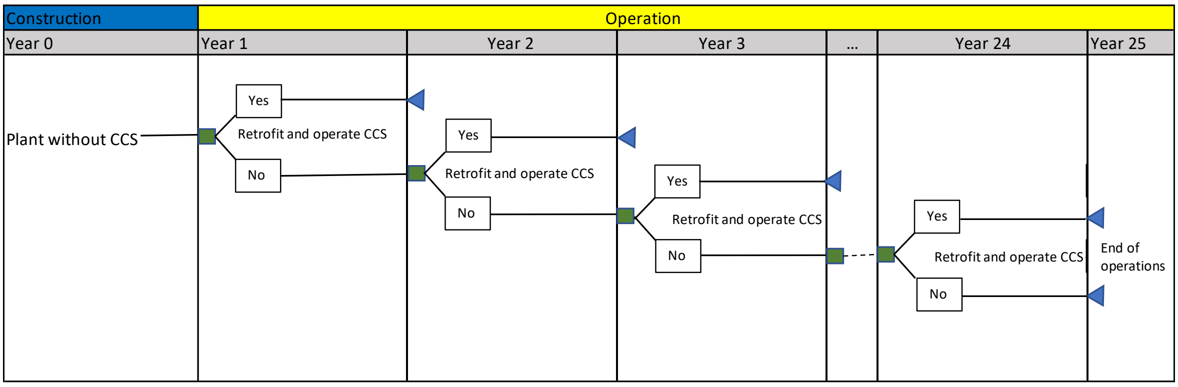
These pathways are illustrated in Figure 5.1 below. Whilst theoretically the decision to exercise, or not, the option could be taken at any time, to simplify the calculations, it is assumed that the decision can only be made once per year.

Figure 5.1: Configuration pathways through the plant life

Case where CCS unit is incorporated at time of building.



Case with option to retrofit CCS



Each of the different configuration pathways will give rise to a different NPV distribution. Whilst the operator will be aware of the current, relevant, costs and prices they cannot be certain as to how these change in the future. Thus, the operator will not know whether exercising the option will or will not result in an increase in 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 as a random decision (provided that it has not already been exercised) in each year of the plant life, with the exception of 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 path the NPV for any path through the decision lattice will be variable, 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.

For each of these configuration pathways, an NPV probability distribution profile can be calculated and statistically characterised. 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 (on the basis of 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 one of a baseline scenario associated with a "fixed system design".

System Description and Economic Performance Assessment Framework

Basis of the Plant Design

The MSR plant used for these calculations is based on one of the designs (case 3; CO_2 capture from the MSR plant's flue gas) described by Collodi and colleagues (Collodi et al., 2017a) and (Collodi et al., 2017b). This design is an MSR plant 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 MSR flue gas is approximately 19%. This compares to the approximately 5% molar concentration in a typical Combined Cycle Gas Turbine plant (Scholes et al., 2016) which makes the capture process more efficient[37].

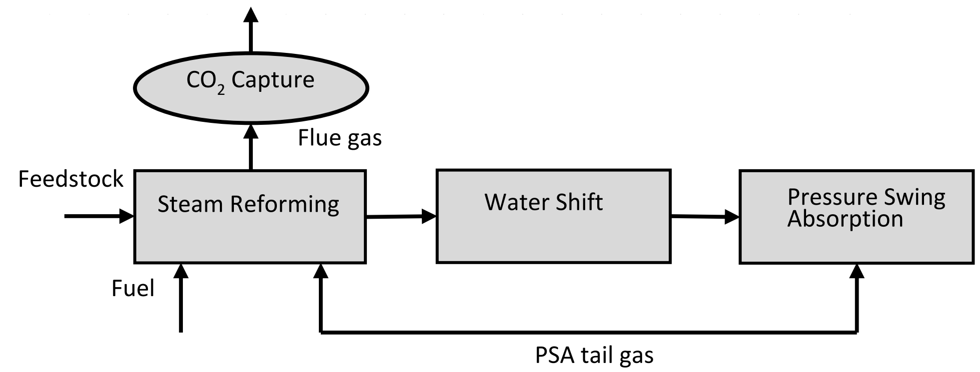
In the MSR process methane, the principal component of natural gas, is reacted with water (as steam) to produce H_2 and CO_2. In the first stage steam is combined with the methane to produce hydrogen and carbon monoxide. The carbon monoxide is then reacted with steam in the presence of a catalyst to 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.

[37] These molar concentrations correspond to approximately 30% and 8% on a mass basis, respectively.

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

The design is for a plant where the CCS unit is incorporated from the beginning, and pricing data are in 2014 euros[38]. Data from other sources was used to supplement this data. This is discussed below:

Figure 5.2 Schematic of the MSR Plant with CCS (Taken from Collodi et al (Collodi et al., 2017b))



Learning Effects

If the CCS plant is fitted after the construction of the MSR 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 MSR unit, this is constructed at the same point in time for all four scenarios and therefore any learning effects affecting the state of the art for MSR plants will have no effect on 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 MSR plant (whether 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 MSR plant, alternative sources of

[38] All cost and price information has been converted into 2020 pounds sterling prior to discounting.

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[39]
- Fixed Operational and Maintenance Costs
- Variable Operational and Maintenance Costs.

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

These costs are given in table 5.1 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 5.1.

Table 5.1 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.

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

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 reduction in cost associated with a doubling of elapsed time) $=1-2^b$.

[39] The amount of electricity that is required for the capture process and therefore is not available for sale.

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 projections 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.

Price of Hydrogen

The NPV of the MSR 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, in some cases, 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 and therefore volatility of the Hydrogen price is not included in the model.

Prices of Natural Gas and Electricity

A major component of the costs that an operator of an MSR will incur is the cost of natural gas used as both a feedstock and as an energy source. Although this analysis is based on the concept of a petrochemical company using its own 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 prices of natural gas 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 large 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 and electricity prices as a consequence of events in the Ukraine as it is not clear what the impact will be over the time scales considered in the main sections of this work. Some scoping calculations have been carried out taking account of the “spike2 in prices following the start of the war in Ukraine. The results of these are reported later in this chapter,

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:

$$Price\ in\ year_N = Price\ in\ year\ _{N-1}\ Growth\ Rate + \ (Price\ in\ year_{N-1}\ \times Random\ term) \quad (2)$$

where the growth rate is the mean annual increase from the time series and 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 values of the growth rate and historical standard deviation are given in Table A3 of Annex A in the Appendix. Three price scenarios have been projected by BEIS (High, Base and Low). For each run of the model a scenario is chosen, and a time series as described above.

The plant is designed to extract excess heat and to 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 is in operation or not. 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 Annex A in the Appendix.

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

Cost of CO_2 Releases**.**
Whether the CCS unit is fitted and in operation or not, the MSR plant will release CO_2 into the atmosphere[40]. The amount released will be significantly less when the CCS unit is fitted and operated. These releases will incur costs for the

[40] The design of SMR plant with CCS used in this analysis (Collodi et al., 2017a) assumes that the efficiency of CO_2 capture is 90%.

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 the Department for Energy and Climate Change[41] (DECC, 2015) to derive growth rates after the end of the BEIS time series.

Additional Costs for Retrofitting

The cost data for both the MSR plant and the CCS unit given by Collodi and colleagues (Collodi et al., 2017a) assume that both components are constructed at the same time. Constructing an MSR plant so that it can accept the retrofitting of a CCS unit at a later date will increase the initial cost. No literature values have been found to quantify this increased cost. Chyong and colleagues (BEI, 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 (Azarabadi & 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. Therefore, this value has been used[42].

Costs of CO_2 Transport and Storage**.**

Costs for the transport and storage of 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 the use of 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.

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). In the case of the two variants with engineering flexibilities, after the first two years of operation, the decision is made as to whether to exercise the associated option. To do this the NPV, for the remainder of the plant life, is

[41] Now part of BEIS.

[42] Prior to consideration of learning effects.

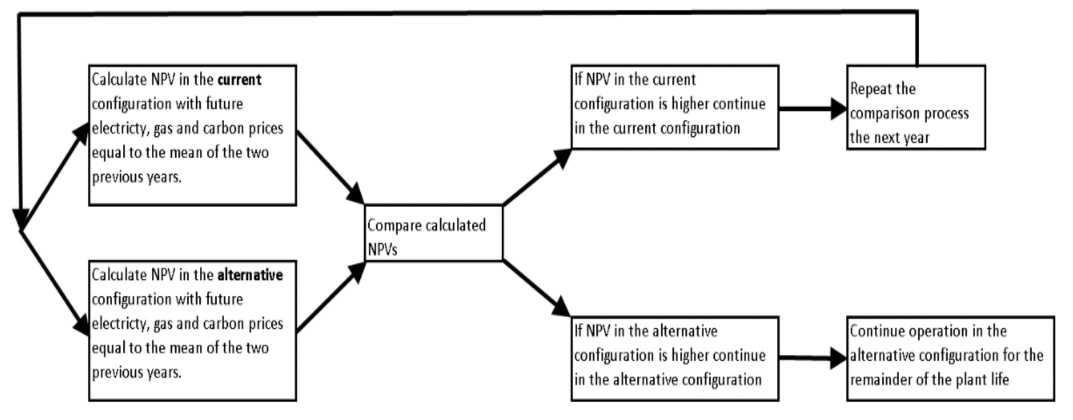
calculated with the plant in its current configuration with the assumption that the prices of gas and electricity remain at the mean of the previous two years for the remainder of the plant life. The NPV, for the remainder of the plant life, is also calculated for the plant with the option exercised with the same assumption regarding constant gas and electricity prices. 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.

If the calculations show that the NPV is greater in the original configuration then the plant is operated in this configuration for the next year and 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.

If the option is exercised the plant is continued to be operated in this configuration until the end of the plant life (i.e., if the decision is made to cease operation of the CCS plant the decision will not be reversed. Similarly, ceasing the operation of a retrofitted CCS plant would not occur.)

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, the SIPMath add in being used to collate the result for iterations. This process is illustrated in the Figure 5.3 below:

Figure 5.3: Flow Chart of the NPV Calculation Process Where a Real Option can be Exercised.



The same process is used for the scenario where there is the option to stop operation of the CCS plant. In the scenarios where there is no option that can be exercised a similar process is used, except the stage where the timing of the exercise of the option is omitted.

Each of the four scenarios and discount rate options were modelled separately.

Capital Costs of the Plant

The capital cost of the plant will depend on which of the plant configurations is constructed. In the cases where there is no CCS unit throughout the life of the MSR plant or where the CCS unit is fitted at the time of the construction of the MSR plant (whether or not there is an option to stop operating the CCS unit) the capital cost is fixed and constant.

The undiscounted capital costs for the cases where the cost is constant are given in Table 5.2 below:

Table 5.2 Undiscounted Capital Costs for Different Plant Configurations

Plant Configuration	Capital Cost (£M)
CCS Fitted at Construction	266
CCS Fitted at Construction with Option to Stop Operation	266
No CCS Throughout Plant Lifetime	149

In the case with the option to retrofit CCS after construction, the capital cost will depend on the time at which the CCS unit is retrofitted (if it is fitted) because of learning effects. This will result in a distribution of capital costs. The mean capital costs are summarised in Table 5.3 below. These results include the incidences where the option to fit the CCS is not exercised.

Table 5.3 Mean Undiscounted Capital Costs for the Case with the Option to Retrofit CCS

	Capital Cost (£M)
All Learning Worlds	167
Maximum Learning Rate World	166
Mean Learning Rate World	167
Minimum Learning Rate World	168

If only those incidences where the option is exercised, the capital costs are as summarised in Table 5.4 below:

Table 5.4 Undiscounted Capital Costs for the Case with the Option to Retrofit CCS; Only incidences where the option is exercised.

	Capital Cost (£M)
All Learning Worlds	268
Maximum Learning Rate World	260
Mean Learning Rate World	268
Minimum Learning Rate World	276

As can be seen, the capital costs where the CCS is retrofitted sometime after construction of the MSR 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 account of learning effects) are 15% higher than the costs of fitting at the time of construction due to these learning effects.

Main Results

Using the proposed real option valuation method, model input uncertainty was propagated through the NPV model and the following probability distribution profiles (depicted in Figures 5.4 to 5.6 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 5.4: Distributions of NPVs with 3.5% Discount Rate

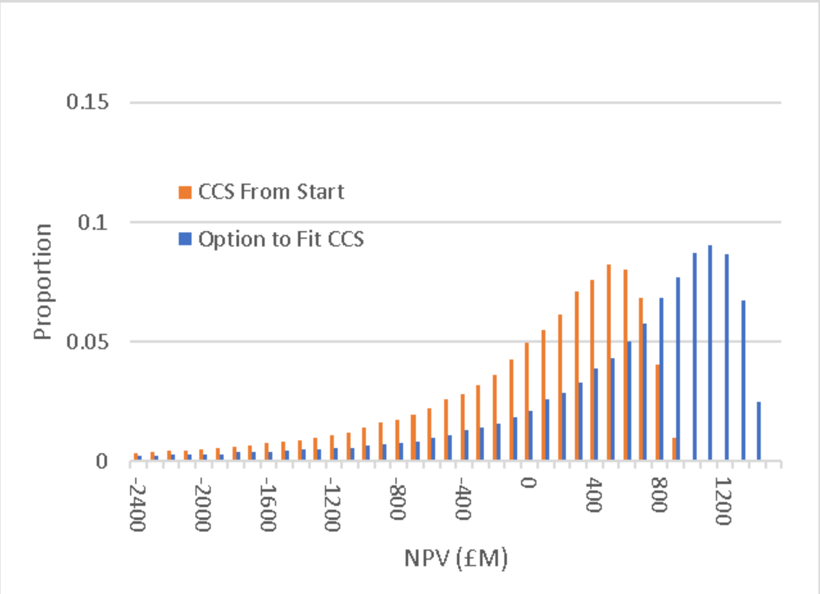


Figure 5.5: Distributions of NPVs with 5% Discount Rate

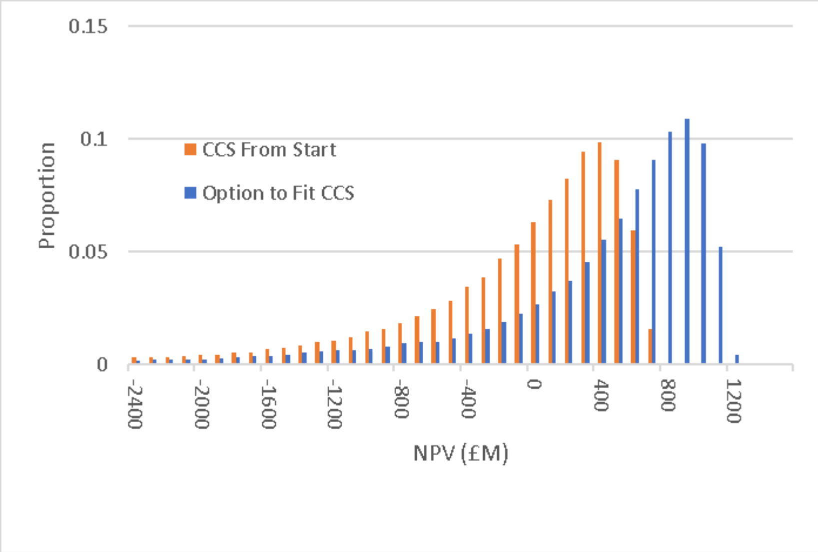
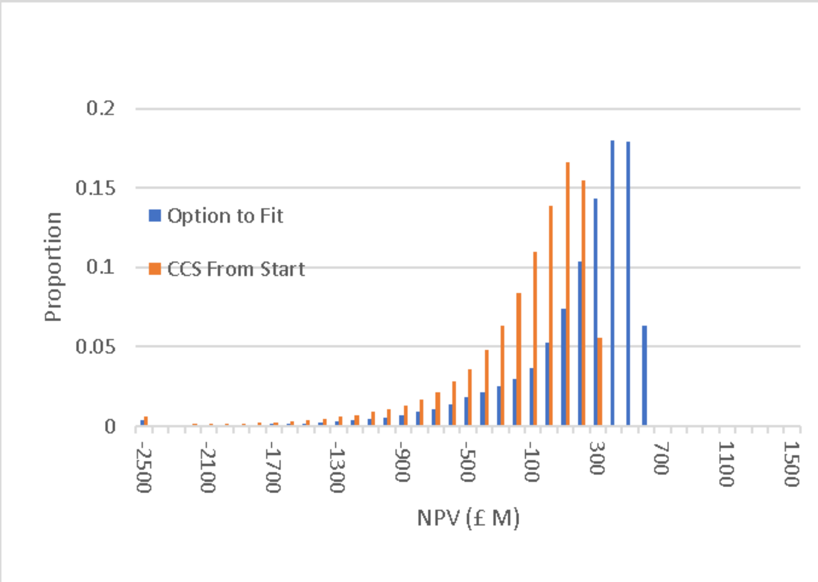


Figure 5.6: Distribution of NPVs with 10 % Discount Rate



Figures 5.7 to 5.9 show the corresponding distributions for the cases where there is no CCS throughout the lifetime of the plant and where there is the option to cease operation of a CCS module during the lifetime of the plant.

Figure 5.7: Distributions of NPVs with 3.5% Discount Rate

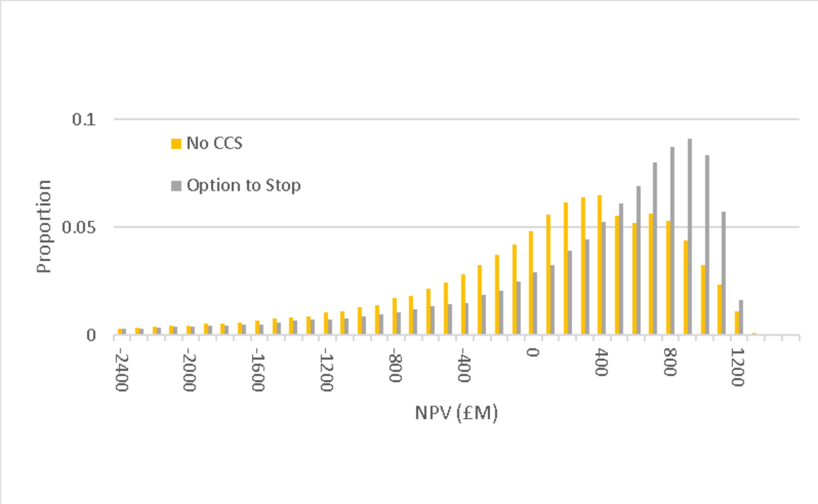


Figure 5.8: Distributions of NPVs with 5% Discount Rate

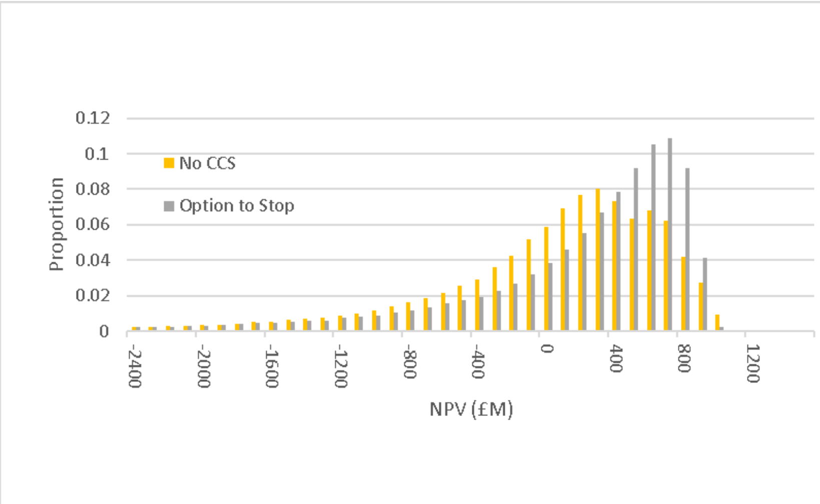
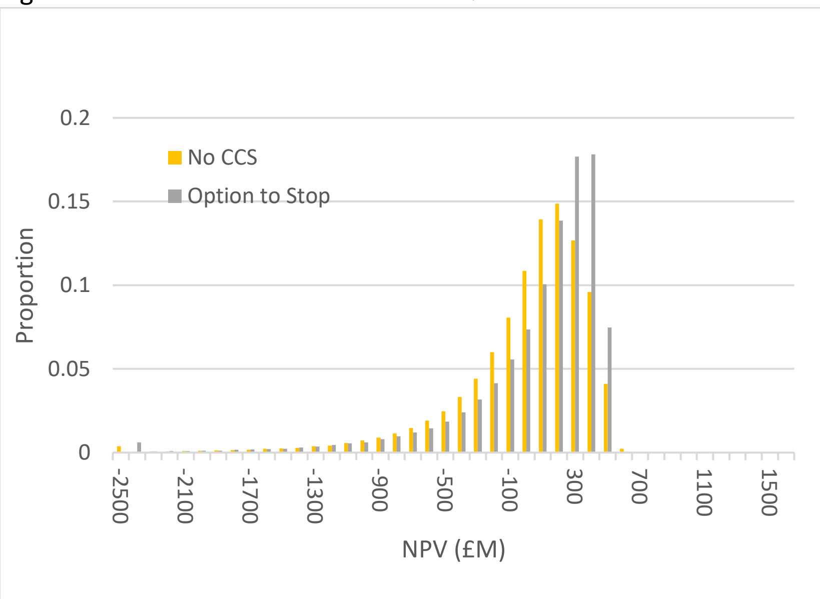


Figure 5.9: Distribution of NPVs with 10% Discount Rate



Some statistics of these distributions are shown in Table 5.5:

Table 5.5: Net Present Values for the Four Cases Considered Using a Range of Discount Rates. The NPV range (plus or minus one standard deviation) are 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
No CCS Throughout Life	Mean NPV (£M)	-174 (-1449, 1101)	-129 (-1110, 835)	-70 (-538, 398)
	Median NPV (£M)	129	104	41
Option to Fit CCS	Mean NPV (£M)	328 (-933, 1589)	247 (-768, 1263)	105 (-375, 585)
	Median NPV (£M)	704	550	250
CCS from Start with Option to Stop	Mean NPV (£M)	63 (-1339, 1465)	11 (-1045, 1066)	-95 (-600, 411)
	Median NPV (£M)	474	328	54

The range (plus or minus one standard deviation) are given in brackets below the mean values.

The values presented above are the mean values for all the three carbon worlds and three 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 Annex B of the supplementary information Appendix.

This increase in average NPVs in the scenarios where there are options that may be exercised gives a value to these options. These values have been calculated by subtracting the mean or median value of the NPV of the corresponding baseline scenario from that of the scenario with the option. These results are summarised in Table 5.6 below:

Table 5.6: Value of the Options to Fit or to Stop Use of 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)	647	529	334
	Median NPV (£M)	623	527	337
Value of Option to Cease Operation of CCS Compared to No CCS	Mean NPV (£M)	237	139	-27
	Median NPV (£M)	346	224	13

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 Annex C of the supplementary information Appendix.

As can be seen from Figures 5.4 to 5.9, the distributions of NPVs are skewed to the left i.e., 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 for 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. The values for the cases where no CCS is fitted at any time during the plant lifetime and the case where there is the option to cease operations of the CCS unit are intermediate to these values with the case with the option to stop operation being the largest of the two cases.

For all four cases (CCS from the start, no CCS throughout the lifetime, option to fit CCS and option to cease operation of the CCS), the NPVs are highest in the low energy world. For the cases where the CCS unit is fitted from the start and where there is no CCS throughout the lifetime of the plant, the NPVs are highest in the low carbon world. This effect is more marked in the case where there is no CCS throughout the lifetime of the facility. For the cases where there are options to fit or cease operation of the CCS unit, changes in the carbon world have little effect on the NPVs.

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 value of the option is greatest in the high energy price world because of the loss of income from the sale of energy needed to operate the CCS. The value of the option is greatest in a high carbon price world.

The option to cease operation of the CCS unit compared to the scenario where no CCS unit is fitted throughout the lifetime has a positive value when carbon prices are high. The values are negative in the low carbon price world, a result of the reduced savings from the cost of carbon emissions compared to the capital cost of the unit. The value of this option is still positive in the base carbon price world, but not as great as in the high carbon price world.

Calculations of Value at Risk and Value at Gain

In order 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 5.7 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 5.7: 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
No CCS Throughout Life	-2290	-1798	-892
Option to Fit CCS	-1875	-1521	-777
CCS from Start with Option to Stop	-2263	-1830	-996

Conversely, the operator could, if future circumstances are favourable, 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 were also calculated. The results of these calculations are shown in Table 5.8

Table 5.8: 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
No CCS Throughout Life	951	766	391
Option to Fit CCS	1258	1008	510
CCS from Start with Option to Stop	1034	792	318

As can be seen the option to be able 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. In the case of the option to cease operation of the CCS unit the value at risk is reduced when compared to the case where no CCS is fitted at any time during the plant lifetime for discount rates of 3.5% and 5%. However, at a discount rate of 10% the value at risk is increased.

For the Value at Gain these values are increased where there is the option to be able to fit the CCS unit during the plant compared to that for the case where the CCS is fitted at construction for all the discount rates considered. In the case of the option to cease operation of the CCS unit the Value at Gain is increased when compared to the case where no CCS is fitted at any time during the plant lifetime for discount rates of 3.5% and 5%. However, at a discount rate of 10% the Value at Gain is reduced.

Correlation of Energy and Carbon Worlds

In the results presented above, no attempt has been made to take account of correlations between the factors that may impact on the calculated NPVs and the values of the options. However, it is likely that there will, 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 5.9 and 5.10 below:

Table 5.9: Net Present Values for the Four Cases Considered Using a Range of Discount Rates. Correlated Cases. The range (plus or minus one standard deviation) are 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
No CCS Throughout Life	Mean NPV (£M)	-124 (-1155, 907)	-135 (-1193, -924)	-74 (-578, 431)
	Median NPV (£M)	72	114	43
Option to Fit CCS	Mean NPV (£M)	331 (-950, 1611)	256 (-746, 1257)	105 (-368, 578)
	Median NPV (£M)	705	554	248
CCS from Start with Option to Stop	Mean NPV (£M)	61 (-1311, 1434)	10 (-1070, 1080)	-89 (-581, 403)
	Median NPV (£M)	473	329	54

The range (plus or minus one standard deviation) are given in brackets below the mean values.

Table 5.10: Value of the Options to Fit or to Stop Use of the CCS Unit with Correlated Energy and Carbon Worlds

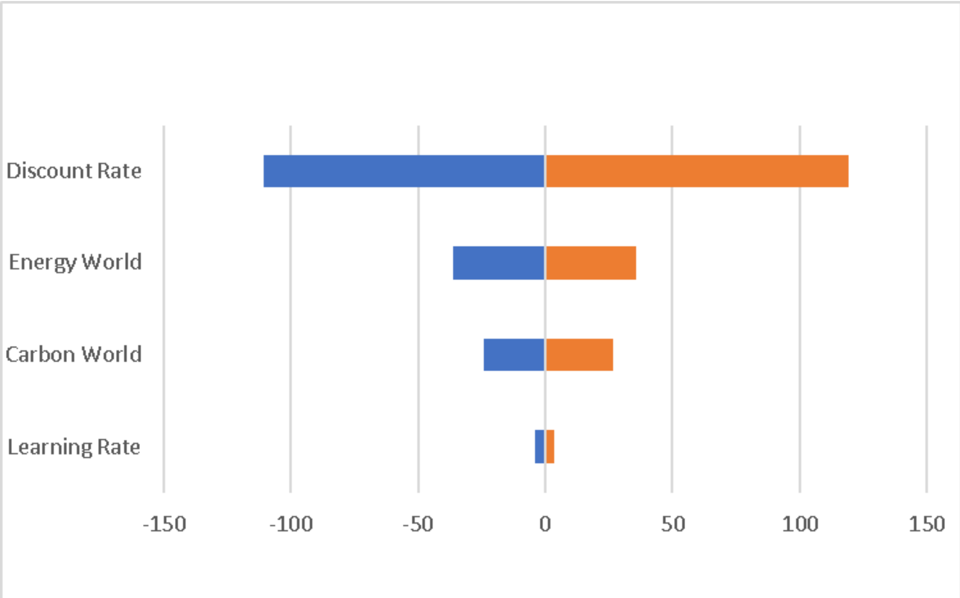
		Discount Rate 3.5%	Discount Rate 5%	Discount Rate 10%
Value of Option to Fit CCS Compared to CCS from Start	Mean NPV (£M)	654	541	332
	Median NPV (£M)	630	533	331
Value of Option to Cease Operation of CCS Compared to No CCS	Mean NPV (£M)	186	144	-15
	Median NPV (£M)	400	214	11

As can be seen, by comparison with the values in Tables 5.5 and 5.6, correlation of the energy and carbon price worlds has little effect on the NPVs or the values of the options. The same pattern of results as is seen in the case where energy and carbon worlds are not correlated, i.e., the mean values of the options are positive except for the case of cessation of the operation of a CCS unit which was fitted at construction.

Sensitivity Analysis

To investigate the impact that the factors (inputs) considered in the model (energy world, carbon world, learning rate[43] and discount rate) have on the calculated value of the options, a sensitivity analysis was carried out using Tornado plots. The distribution of the values of the option were calculated separately for each of the values of the main parameters (discount rate, carbon world, energy world and learning rate world). The other parameter values were allowed to vary randomly. The mean values of the distribution for each value of the parameter are shown in the Tornado plots below. The plots are given in Figures 5.10 and 5.11 below for the cases where the energy and carbon price worlds are not correlated. Figures 5.12 and 5.13 show the sensitivity for the corresponding correlated cases.

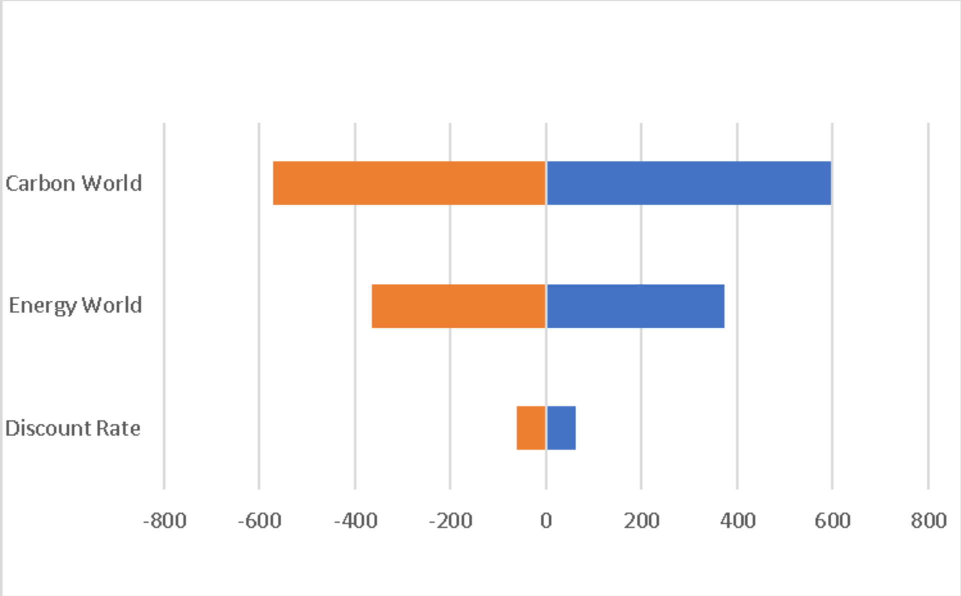
Figure 5.10: Sensitivity of Value of Option to Fit CCS to Input Parameters



The sensitivity of the calculated value of the option of the magnitude of the additional costs involved in designing and constructing the plant to be able to be retrofitted with the CCS plant and the additional costs of retrofitting the plant compared to fitting it at the time of construction were also included in the analysis. These factors were found to have negligible effect and therefore are not included in Figure 5.10 for clarity.

[43] Learning rate is not relevant for the option to stop the operation of the CCS unit.

Figure 5.11: Sensitivity of Value of the Value of the Option to Stop CCS to Input Parameters



As can be seen, in the case of the option to fit the CCS unit after construction, the most impactful model input on the value of the option is the discount rate. The prices of energy and carbon releases have a lesser effect. The learning rate has little, if any, impact on the option value.

In the case of the option to stop the use of the CCS unit, the cost of energy and the cost of releasing CO_2 has the highest impact with the discount rate having a mild effect.

Figure 5.12: Sensitivity of Value of Option to Fit CCS to Input Parameters: Correlated Energy and Carbon Worlds

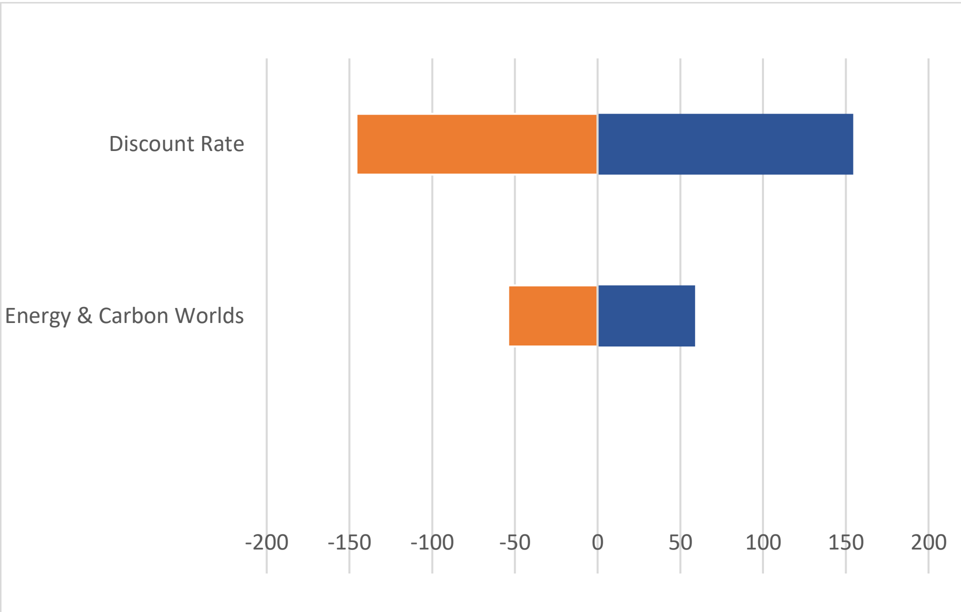
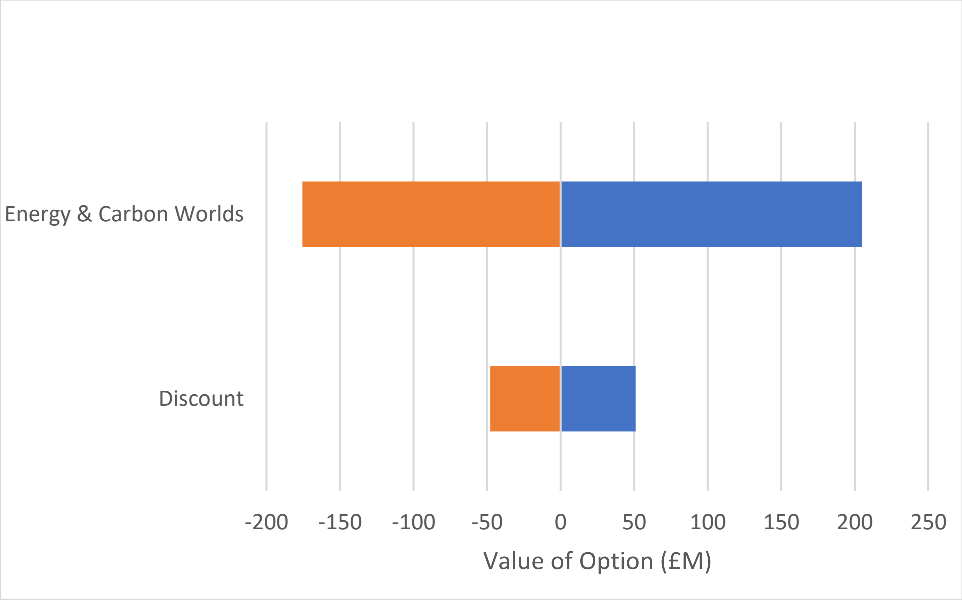


Figure 5.13: Sensitivity of Value of Option to Stop CCS to Input Parameters: Correlated Energy and Carbon Worlds



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

Additional Analyses

During the development of the model, and the performance of the analyses several areas were identified where alternative options could have been explored in the main analyses. These are considered below:

Higher than Envisaged Energy Prices.

The prices of electricity, gas and hydrogen used in the calculations were derived from predictions, made by others, and assumed that there would be no major perturbations in the prices, only variability similar in magnitude to those seen in the recent past. However, the start of Russian military operations in Ukraine in February 2022 led to sharp increases in the prices of both gas and electricity. Whilst it is not clear whether these increases will be sustained, it raises the question as to whether the conclusions described previously as to the value of the engineering flexibilities would hold in such changed circumstances.

The time series, for natural gas and electricity prices[44], used in the original versions of the model were replaced with data sourced from The Office of Gas and Electricity Markets (ofgem, 2022.). The graphs from this source were digitised using the plotdigitizer app (Plotdigitizer (2023)). Mean prices for the period 22nd February 2022 (the date of commencement of Russian military operations) to 26th

[44] Data for prices of hydrogen and carbon credits were not readily available.

September 2022 were calculated and these values, with the same amount of variability as used previously, were used for the rest of the plant life. None of the other assumptions and data sources were changed.

The results of these calculations (referred to as "Ukraine" calculations) are given in Tables 5.11 to 5.16 below.

Table 5.11 Net Present Values for the "Ukraine" Scenario Compared to the Values Calculated for the Base Scenario: 3.5% Discount Rate.

		Discount Rate 3.5%	
		Mean (£M)	Median (£M)
Option to Fit	Prices used in Main Text	328	704
	" Ukraine" Prices	-3602	-2022
CCS From the Start	Prices used in Main Text	-319	81
	" Ukraine" Prices	-612	788

Table 5.12: Net Present Values for the "Ukraine" Scenario Compared to the Values Calculated for the Base Scenario: 5% Discount Rate.

		Discount Rate 5%	
		Mean (£M)	Median (£M)
Option to Fit	Prices used in Main Text	247	550
	" Ukraine" Prices	-2950	-1734
CCS From the Start	Prices used in Main Text	247	22
	" Ukraine" Prices	-698	1120

Table 5.13: Net Present Values for the "Ukraine" Scenario Compared to the Values Calculated for the Base Scenario: 10% Discount Rate

		Discount Rate 10%	
		Mean (£M)	Median (£M)
Option to Fit	Prices used in Main Text	105	250
	" Ukraine" Prices	-1655	-1118
CCS From the Start	Prices used in Main Text	-229	-88
	" Ukraine" Prices	-436	198

Table 5.14: Value of the Option to Retrofit CCS for the "Ukraine" Scenario Compared to the Values Calculated for the Base Scenario:3.5% Discount Rate

		Discount Rate 3.5%	
		Mean (£M)	Median (£M)
Value of the Option	Prices used in Main Text	647	623
	" Ukraine" Prices	-2989	-2810

Table 5.15: Value of the Option to Retrofit CCS for the "Ukraine" Scenario Compared to the Values Calculated for the Base Scenario: 5% Discount Rate

		Discount Rate 5%	
		Mean (£M)	Median (£M)
Value of the Option	Prices used in Main Text	529	527
	" Ukraine" Prices	-2252	-2855

Table 5.16: Value of the Option to Retrofit CCS for the "Ukraine" Scenario Compared to the Values Calculated for the Base Scenario: 10% Discount Rate

		Discount Rate 10%	
		Mean (£M)	Median (£M)
Value of the Option	Prices used in Main Text	334	337
	" Ukraine" Prices	-1219	-1317

As can be seen from the above tables use of these higher electricity and gas prices results in significant reductions in the NPV for the case where the option to retrofit a CCS plant is available and a corresponding decrease in the value of the option as a result of the loss of income associated with the energy needed for the operation of the CCS plant. However, this may not be the case if there are corresponding increases in the price of hydrogen and carbon credits in light of the increases in gas and electricity prices.

Alternative Decision Rule**.**

The original calculations of the value of the option were made on the basis that the option to retrofit the CCS plant is exercised if the calculations show that this is likely (based on the historical cost and price data) would give a higher NPV in the case where the option is not exercised. This means that, in theory, the option could be exercised if the assessed benefit was as little as £1. Given that the calculated values are uncertain it is possible that the operator may decide not to exercise the option for such a small, apparent, advantage.

To investigate what impact a more conservative approach to the decision on exercising the option might have, a version of the model was constructed where the option is exercised only when the calculations show that exercising the option would increase the NPV by at least 10%. The results of these calculations are shown in Table 5.17 below:

Table 5.17: Value of the Option to Retrofit the CCS Plant with the Modified and Original Decision Rules.

	Discount Rate 3.5%		Discount Rate 5%		Discount Rate 10%	
	Mean (£M)	Median (£M)	Mean (£M)	Median (£M)	Mean (£M)	Median (£M)
Ten % Decision Rule	325	706	255	553	105	250
Original Decision Rule	328	704	247	550	105	250

These results show that this change in the decision rule has little, if any, effect on the calculated values of the options.

Similarly, it was not clear that an explicit decision rule is needed to determine whether to exercise the option when attempting to calculate the value of the options. Instead, the exercising of the option could be modelled as a random occurrence with it having equal possibility of occurring in each year of plant operation (provided it has not already been exercised). To investigate what effect this absence of an explicit decision rule what have on the calculated results a variant of the model was constructed with this random decision.

The results of this comparison are shown in Table 5.18 below.

Table 518: Comparison of Calculated Value of the Option to fit CCS with and without Explicit Decision Rules.

	3.5 % Discount Rate		5 % Discount Rate		10 % Discount Rate	
	Mean	Median	Mean	Median	Mean	Median
With Decision Rule	328	704	247	550	105	250
Without Decision Rule	203	566	157	436	61	188

As can be seen the inclusion of an explicit decision rule increases the value of the option to retrofit the CCS plant.

Chapter Conclusions

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

In a conventional discounted cash flow approach to economic performance assessment of the facility is typically based on the assumption that the decision to install and operate 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 environment (macro-economic, regulatory etc.,) thereby missing opportunities to respond proactively, thus accessing upside value-enhancing prospects and/or limit exposure to downside value-eroding risk and losses. Instead, by creatively identifying flexible system design options that allow pro-active adjustment to evolving conditions as uncertainties progressively resolve themselves, the management team create valuable options to operate the process. These engineering flexibilities give increased value which can be quantified using a real options approach.

In this chapter a structured approach has been used to identify such design flexibilities and value the option of exercising them using an integrated real options and Monte-Carlo simulation approach. The proposed method allowed a potentially insightful economic performance assessment of flexible design options for blue hydrogen production under various sources of uncertainty demonstrating that exercising flexibility could generate considerable value over the facility's lifetime. In particular, in both cases where flexibility was realised, through the ability to retrofit the carbon capture unit sometime after construction ("construction flexibility") or to cease operation ("operational flexibility") 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 options 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.

Whilst this analysis has considered the case of a steam methane reformation plant producing hydrogen from natural gas, the engineering flexibilities / real options approach is equally appropriate to the consideration of a fusion small modular reactor. This analysis is performed in Chapter 6 where it is considered in combination with a portfolio approach to a fleet of such fusion reactors with different engineering flexibilities.

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Chapter 6: Combining Engineering Flexibilities with a Portfolio Approach

The arc of this thesis so far has been to move from a relatively simple means of assessing the economic value of a fusion Small Modular Reactor (SMR) (or another asset) to more complex economic methodologies. Chapter 4 considered the simple case of a fusion SMR supplying electricity to the grid and used the concept of Net Present Value to assess the value. Chapter 5 then progresses to consider the use of engineering flexibilities and real options and how these impacts on the NPV. Whilst in this case, the plant considered is a Methane Steam Reformation plant used to produce hydrogen from natural gas the analysis is of relevance to the consideration of a fusion SMR. In this chapter, the previous approach is extended to make use of a more complex approach. This approach the concept of NPV (Chapter 4) is combined with the use of engineering flexibility / real options (Chapter 5) in conjunction with the use of a portfolio approach. It also returns to considering a fusion SMR (although the approach may be of wider applicability).

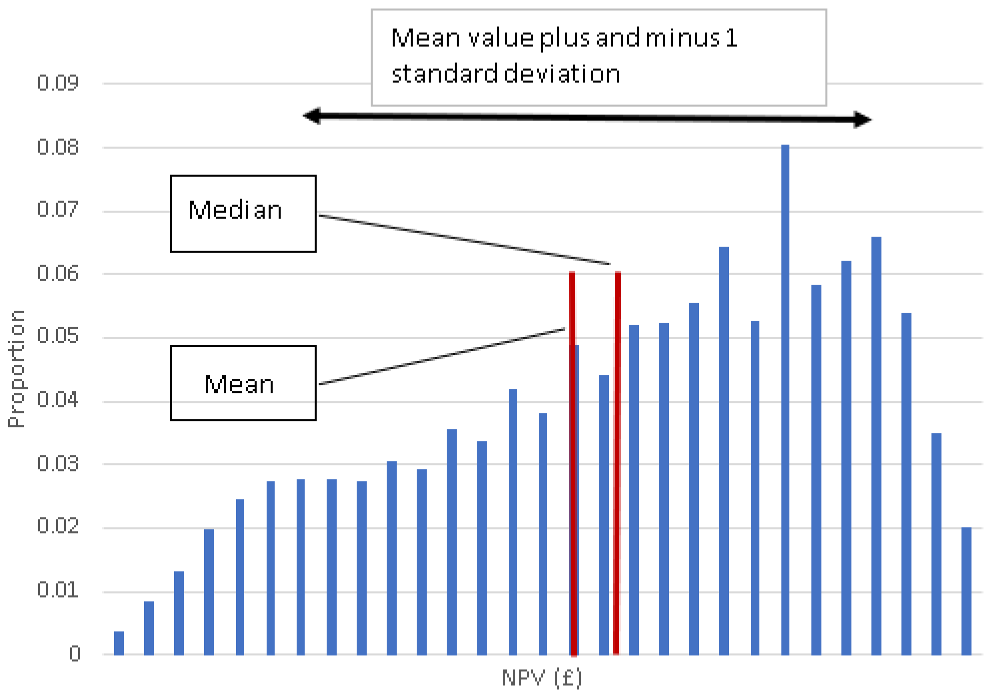
The consideration of engineering flexibilities/real options has been limited to cases where there is one available option either the option to retrofit a CCS unit to a MSR plant originally constructed with the flexibility to be modified in this way, or the option to stop operating a CCS unit in a plant constructed with one. The use of a portfolio approach allows the consideration to be extended to the scenario where there are two or more engineering flexibilities.

At a simple level a fusion SMR can be considered as a source of energy that can be applied to a range of applications other than the supply of electricity to a grid. A discussion of these alternative applications can be found in Chapters 1 and 2. Any choice of technology and hence “product” used to employ the energy produced by a fusion SMR requires that an *a priori* decision is made by the developer as to which of the possible options would offer the largest return on their investment despite this being, in part dependent on prices many years in the future. This exposes the developer to the risk that they will have made the wrong decision and miss the best return or the opportunity to minimise their loss. The use of an engineering flexibility / real options approach has been examined and shown to reduce this risk, as shown later in this chapter.

Application of Portfolio Theory To Fusion SMRs

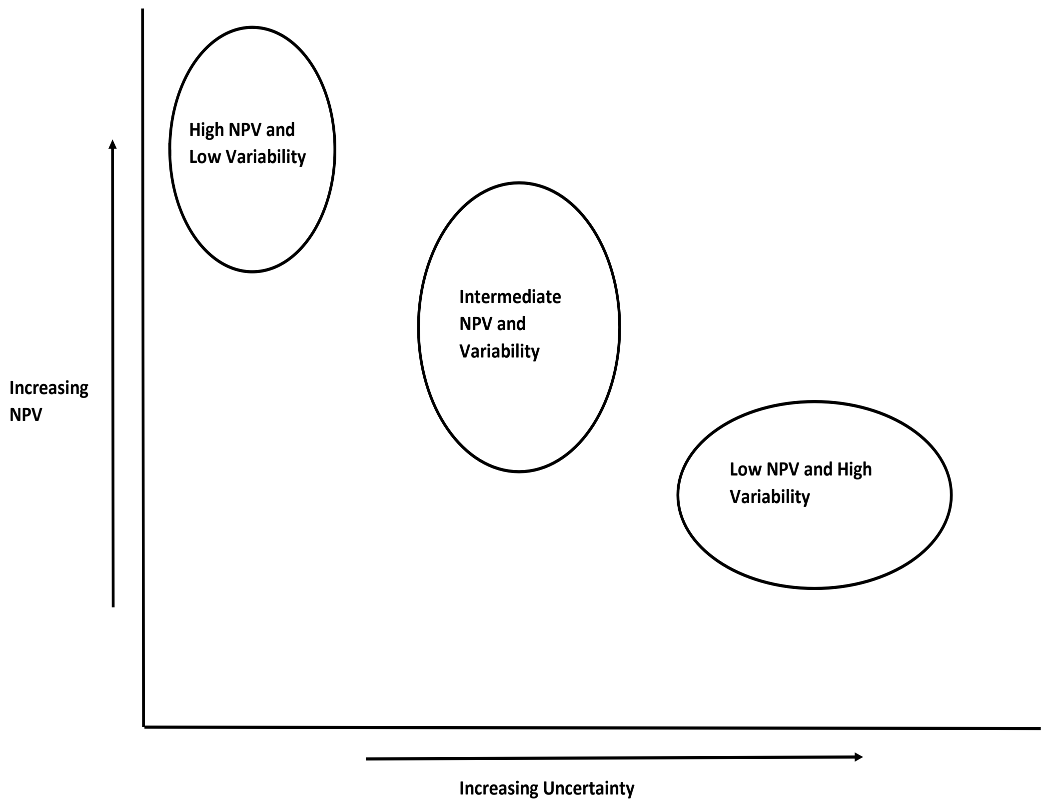
In this approach, instead of the developer constructing a fleet of plants designed and operated to produce a single “product”, the fleet is constructed to consist of two or more types of plant with different products. This enables the operator to take advantage of higher prices for one “product” or to mitigate against the risk of a lower than expected price. Depending on the mix of the types of plant in the fleet, each portfolio will have different NPVs if the input parameters used in the calculations are deterministic i.e., there is no variability in their value, the calculated NPVs will also be deterministic. If, however, there is a probabilistic element to the model inputs (as detailed below) each iteration of the model will give a different result for the NPV. Repeated iterations of the model result in a distribution of results. This distribution can be characterised by a number of statistics. These are illustrated in Figure 6.1 below.

Figure 6.1 Illustrative Distribution of Calculated Net Present Values (Illustrative values only)



The standard deviation gives an indication of how closely the values are dispersed around the mean value. A low standard deviation means the values are closely clustered around the mean. In this specific case, it represents the degree of confidence the operator has that they will obtain the anticipated return. Each portfolio will have its own combination of mean NPV values and standard deviation in these. This combination can be illustrated by plotting the mean NPV values against the standard deviation in these values, as shown in Figure 6.2 below:

Figure 6.2 Combinations of NPVs and Standard Deviations in NPV



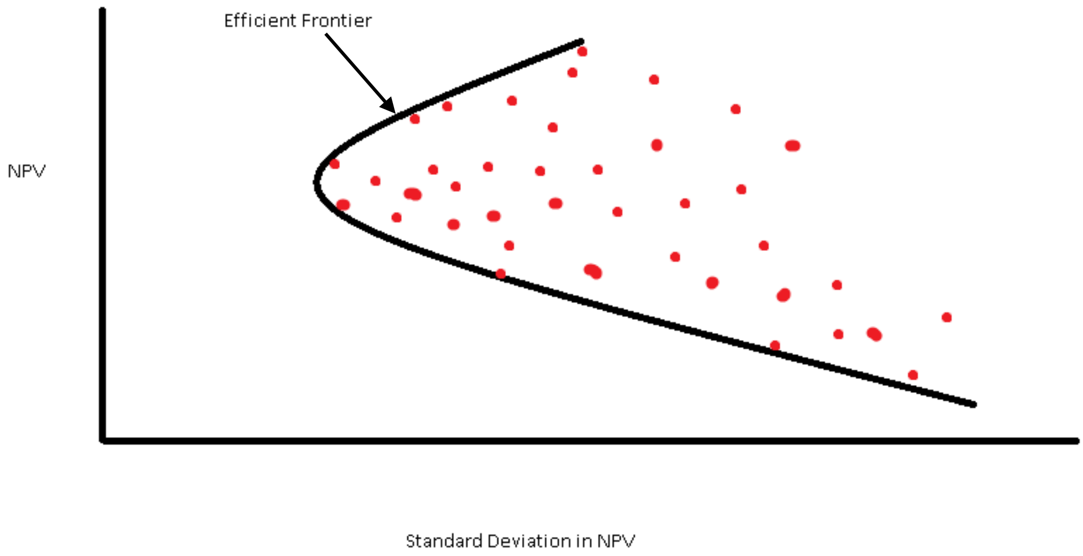
Combinations of NPV and standard deviation in the NPV resulting in points to the top left represent portfolios with high NPVs and low uncertainty in these values. Conversely, combinations giving points to the bottom and left represent portfolios resulting in low NPV and with a high degree of uncertainty.

This distribution of combinations of NPV and the standard deviation in the NPV[45] gives rise to the concept of the efficient frontier. This concept originates with the

[45] Other means of quantifying the value and uncertainty associated with this value may be used.

work of Markowitz (Markowitz, 1952)[46]. This can be defined as delineating those portfolios that result in the highest returns for given level of risk or, conversely the lowest risk for a given return. This is illustrated in Figure 6.3 below:

Figure 6.3 Definition of the Efficient Frontier (Schematic Representation).



Points to the right of the curve would be regarded by most investors as being sub-optimal as they relate to portfolios that have a higher risk for the rate of return (NPV). The optimum combination of NPV and uncertainty in the NPV depends on the risk tolerance of the developer.

Incorporation of Engineering Flexibility and Real Options

In this section the two approaches, the use of engineering flexibilities with real options and a portfolio approach are combined. A developer of fusion SMRs is unlikely to procure a single plant. It is more likely that the developer will procure a fleet of plants. The developer also has the choice whether or not to incorporate an engineering flexibility in the plants. As has been shown in Chapter 5, the use of such flexibilities give rise to real options that allow the operator to respond proactively to changes in costs and prices to maximise their return. The engineering flexibility does not have to be incorporated in all of the plants and different flexibilities could be incorporated in plants.

[46] Markowitz doesn't use this exact term in this paper.

Thus, a fleet of a fixed number[47] of fusion SMRs could consist of different combinations of different variants, some without any flexibility, some with a flexibility of one type and some with another type of flexibility[48]. Each combination of fusion SMR variants constitutes a different portfolio. Depending on how costs and prices develop in the future each portfolio will have its own combination of mean NPV and the uncertainty in this mean NPV.

This section builds upon the work described in Chapter 5 dealing with the use of engineering flexibilities/real options with a steam methane reformation plant. The methodology described there is applicable to the case of a fusion SMR with engineering flexibility. Once again, the approach of Cardin (Cardin, 2013) has been used to identify potential flexibilities. This approach is summarised in four stages:

1. *Identification of Baseline Design:* In this case, the baseline design is a fusion SMR designed and operated to provide electricity for the grid.
2. *Recognition of Uncertainty:* Uncertainties that impact on the NPVs are the prices that may be obtained for the various potential "products" that the plant could produce.
3. *Generation of Concepts:* This consideration of the uncertainties leads to the identification of two potential candidates for plants with engineering flexibilities. These are:

   A fusion SMR plant that can either sell the electricity generated to the grid or be retrofitted with electrolysis plant for production and subsequent sale of hydrogen.

   Secondly discussions with Professor Konishi at the Anglo-Japanese Juno workshop held in Cambridge in June 2019 highlighted the possibility of using a fusion SMR as the energy source for a plant sequestering CO_2 from biomass. This led to the concept of a fusion SMR with the engineering flexibility to be able to accept the

[47] In this work a fleet size of 10 fusion SMRs has been chosen. This choice is arbitrary and other fleet sizes could be used.
[48] Again, the choice of 2 types of flexibility (and hence 3 variants of fusion SMRs) is arbitrary and more types of flexibility could be considered.

installation of a sequestration plant and obtain an income from this "product".

4. *Design Space Exploration:* The initial plant design is amended so that it is possible for the necessary technology to be retrofitted for the production of the alternative products and the relevant additional cost date obtained. The design of these plants and the associated plants are described below.

The return to the developer of the fusion SMR can be quantified by the Net Present Value (NPV) of the plant and any associated technology. The NPV is the, time-discounted, sum of future flows of incomes and costs as given by Equation 1 below:

$$NPV = \sum_{t=1}^{n} \frac{I_T}{(1-r)^t} \qquad (1)$$

Where I_t is the net income (i.e., income less costs) in year t

t is the year

and r is the discount rate.

The calculated NPV is sensitive to the discount rate which reflects the time preference value of money – in that reduced value is placed on incomes and expenditures that are incurred in the distant future compared to those incurred at closer times. In the calculations presented here, three values for the discount rate have been used, 10%, 5% and 3.5%. These are different discount rates than were used in Chapter 4. The rates used here were selected to a range of possible discount rates. The values used in Chapter 4 were selected to reflect the values that have been used (or postulated to be used) for other nuclear projects, that rate recommended by HM Treasury and the rate it was believed that the Government could borrow.

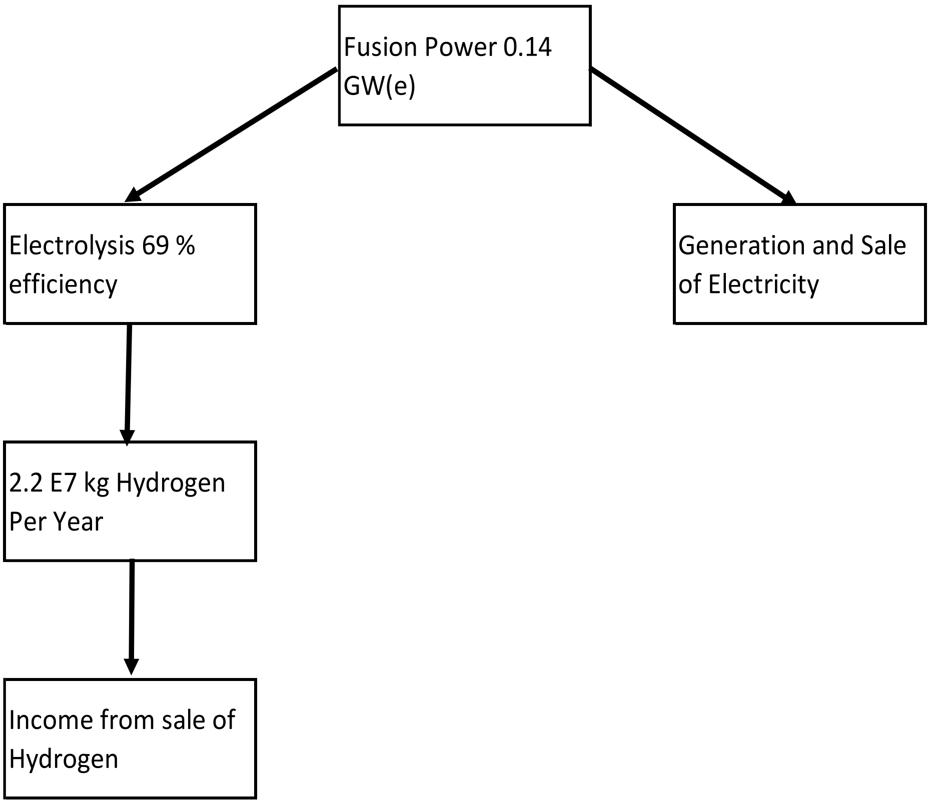
Plant with Flexibility to be Retrofitted for Electrolysis

The first concept for a plant with flexibility for inclusion in a portfolio is a fusion SMR initially designed and constructed to generate electricity for sale to the UK grid, with the capability of being retrofitted of an electrolysis plant for the production of hydrogen from water. Costs and operational data for the fusion SMR plant are the same as those used in Chapter 4 but scaled to be for a single module plant. The capital costs have also been increased by 3% to reflect the additional costs associated with being able to be retrofitted, in line with the assumption used in Chapter 5.

Cost data for the electrolysis plant has been obtained from the World Energy Council (World Energy Council, 2021) This source gives upper and lower time series estimates of the price of electrolysis plants[49] in terms of 2020 US$ per kW. These costs have been scaled to the output of a single fusion SMR and converted to 2020 £[50]. A mean cost time series was constructed from these two time series. The costs have been increased by 15% to reflect the additional costs involved in retrofitting, compared with the costs of installing the plant at the time of construction as recommended by Azarabadi and Lackner (Azarabadi & Lackner, 2020) in the case of retrofitting a direct air capture plant. For each run of the model a high, mean or low time series for the cost of retrofitting the plant is randomly selected. Data on the operating costs, efficiency etc. were obtained from the Organisation for Economic Co-operation and Development (OECD-NEA, 2022). The conceptual model is shown in Figure 6.4 below:

[49] In this case Proton Exchange Membrane electrolysis
[50] As have all cost data used in this analysis.

Figure 6.4: Conceptual Model of the Plant with Flexibility to Switch to Hydrogen Production



No account has been taken of planned and unplanned shutdowns in these values.

Projections of future electricity prices were obtained from the UK Department for Business, Energy and Industrial Strategy (BEIS, 2022) .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.

A time series of electricity 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:

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

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

As has been pointed out by Corbeau (Corbeau, 2022) there is a dearth of historical data relating to the price of hydrogen[51]. This means that deriving the historic variability in hydrogen price for incorporation in forecasts of future prices as has been done for electricity prices is not feasible. Instead use has been made of hydrogen price predictions from Aurora (Aurora Energy Research, 2023). This prediction incorporates a range for possible prices, and this has been used to estimate variability for incorporation in a geometric Brownian motion model for future hydrogen prices.

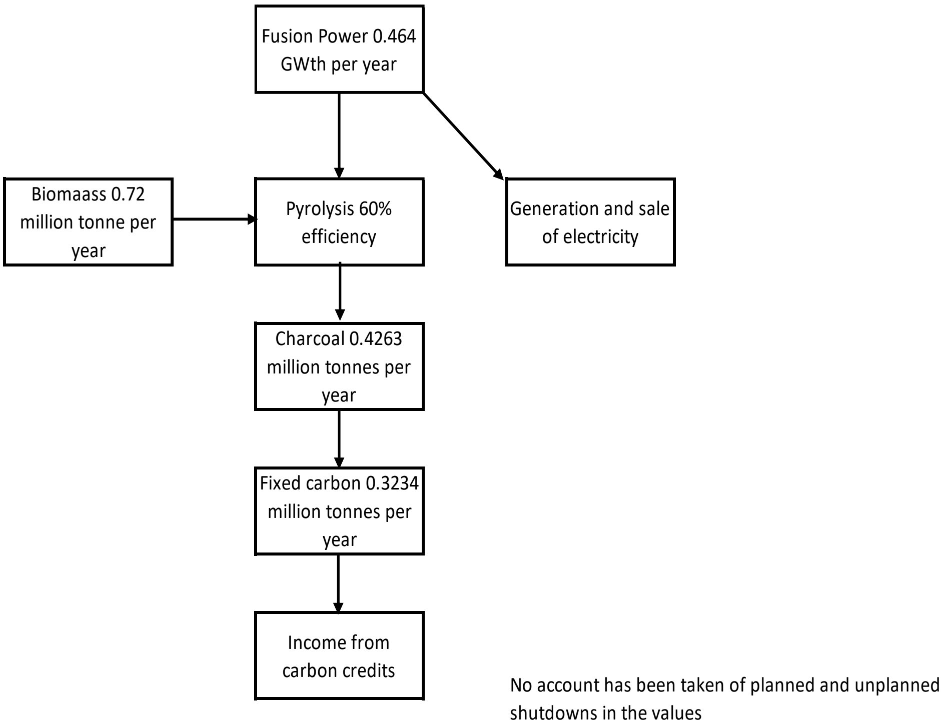
Plant with Flexibility to be Retrofitted for Carbon Sequestration

The second concept is based on the work of Konishi and colleagues as described by Nam and colleagues (Nam et al., 2020)and by Takeda (Takeda, 2019). In this concept the fusion SMR is designed and constructed with the flexibility to be able to be retrofitted with a pyrolysis for the sequestration of CO_2 from a range of forms of biomass. The costs for the fusion SMR module are the same as for the first concept. Cost data for pyrolysis plants of varying capacities was obtained from the work of Shackley and colleagues (Shackley et al., 2011). A linear regression was fitted to this data to allow capital cost data to be derived for a pyrolysis plant sized to match the output of the fusion SMR module. Unfortunately, no information is available as to how the costs may reduce over time as a result of learning effects. Operating costs were also obtained from the same source. The “product” in this scenario is the credits received for the sequestration of CO_2. Data for the value of these credits were obtained from the Department of Business, Energy and Industrial Strategy (BEIS, 2019). This data comprises three time series, high, mean and low. The decision as to which time series to use in each iteration of the model is made randomly. It is assumed, for this model, that the biomass is waste product which is obtained at no cost (e.g., waste biomass obtained from a recycling service).

This conceptual model is illustrated in Figure 6.5 below:

[51] I am grateful to Professor Kazantzis for bringing this reference to my attention.

Figure 6.5: Conceptual Model of the Plant with Flexibility to Switch to Sequestration



<u>Decision Rule for the Exercising of the Option</u>

The operator of the plant will only exercise the option provided by the engineering flexibility if it appears that the additional costs involved in doing so are compensated for by the additional income. In each year of the operation of the plant (except for the first two years and the last year of operation) calculations are made of the future net income of the plant with and without the option exercised based on the assumption that the relevant prices and costs in the future are the same as the mean of the previous two years. If these calculations show that exercising the option will result in a greater income than will be obtained if the option is not exercised, then the option is exercised. If the decision is not to exercise the option, then the process is repeated in the next year.[52] This decision rule is described in Equations 3a and 3b and Figure 6.6 below.

[52] Other decision rules could be used, for example, the option is only exercised if the net income with the option exercised is more than x% greater than the income with the option being exercised as has been done in Chapter 5.

If:

$$\sum_{n=t+1}^{n=30} O_{et}\left(\frac{P_{t-1}+P_t}{2} - C_e\right) \geq R_t + \sum_{n=t+1}^{n=30} O_{at}\left(\frac{Q_{t-1}+Q_t}{2} - C_a\right) \qquad (3a)$$

The option is not exercised, and the plant continues to generate electricity.

However, if:

$$\sum_{n=t+1}^{n=30} O_{et}\left(\frac{P_{t-1}+P_t}{2} - C_e\right) < R_t + \sum_{n=t+1}^{n=30} O_{at}\left(\frac{Q_{t-1}+Q_t}{2} - C_a\right) \qquad (3b)$$

The option is exercised, and the plant is adapted to produce the alternative for the remainder of the plant's lifetime.

Where t is the year

O_{et} is the output of electricity in year t

O_{at} is the output of the alternative product in year t

P_t is the price of electricity in year t

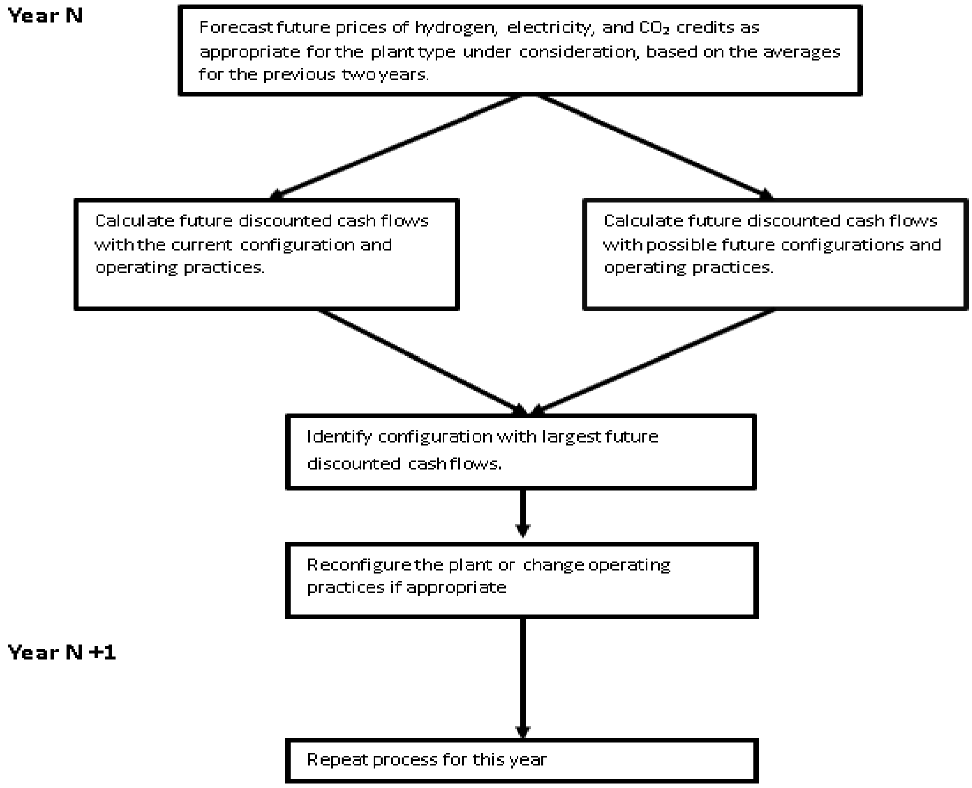
Q_t is the price of the alternative product in year t

R_t is the cost of retrofitting the alternative technology in year t.

C_e is the operating cost for an electricity plant per year, assumed to be constant.

C_a is the operating cost for a plant producing the alternative product per year. Similarly this is assumed to be constant.

Figure 6.6 Flow Chart of Decision to Exercise Option or Not



As a consequence of the stochastic nature of some of the costs and prices it is unlikely that future costs and prices will be the same as the mean of the previous two years. It is therefore possible that, in hindsight, the decision to exercise the option was mistaken and has reduced the value of the plant. There is no facility within the model to reverse the decision to exercise the option.

The nature of the decision rule is such that if the decision is made to exercise the option for one type of plant, then it is not necessarily made to exercise the corresponding option for the other type of plant.

Construction of the Portfolio

The portfolios are constructed so as to have a total of ten plants consisting of a mix of three types:

- Plants which are constructed and operated to generate electricity for sale to the grid. For these plants the additional 3% capital costs to allow for retrofitting of alternative technologies are not included.

- Plants constructed to generate electricity but with the engineering flexibility to be retrofitted with an electrolysis plant for the production of hydrogen.
- Plants constructed to generate electricity but with the engineering flexibility to be retrofitted with a pyrolysis plant for the sequestration of CO_2 from biomass.

The components of the portfolio are selected randomly from the three types so that it is possible for a portfolio to consist exclusively of one type of plant.

Implementation of the Model

The models were constructed as a series of interlocked Excel spreadsheets. The SIPMaths Excel add-in (Savage et al., 2017) was used to randomly sample the probabilistic input parameters and to collate the results. The models were run for 200,000 iterations to give distributions of the NPVs so that there are sufficient data points for each of the possible portfolios for statistics to be derived. The decision to use SIPMaths rather than probably better known commercial tools such as @Risk (Palisade, 2023) or Crystal Ball (Oracle Corporation, 2023) was predominately motivated by the ability to “get under the bonnet” of the software to ascertain, if necessary, what the software was doing, an ability not so readily available with the commercial products.

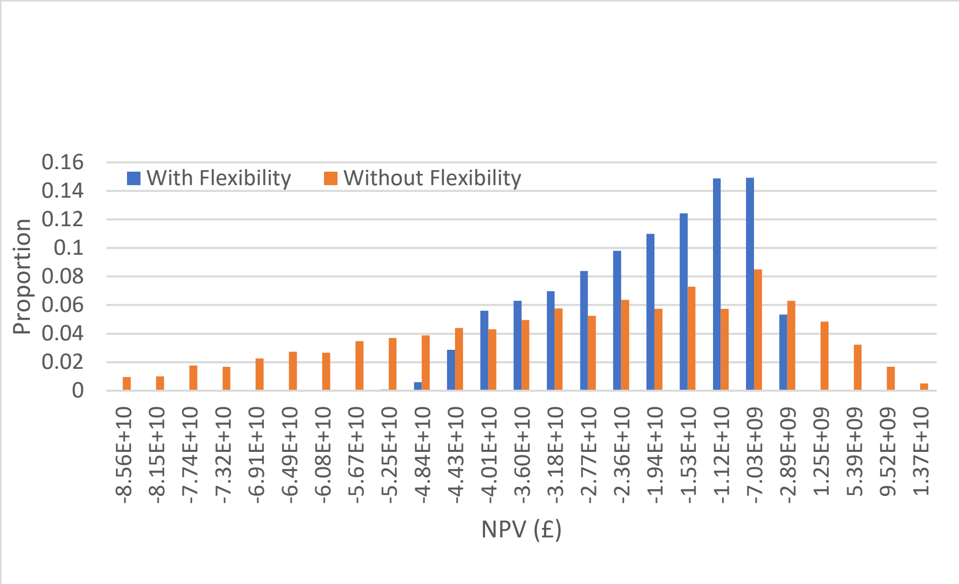
A flow diagram of the model is given in Annex F of the Appendix

Results of the Calculations

Median and mean values of the NPV and its standard deviation were performed for three different discount rates (10%, 5% and 3.5%) during each iteration of the model. The Value at Risk (the 5th percentile) capturing the potential for downside risk, and the Value at Gain (95th percentile) capturing the potential for upside opportunities were also calculated. These are presented for all three discount rates in Tables 6.1 and 6.2 below and with a greater degree of granularity in the additional information Annex E of the Appendix. The results are also presented in graphical form in Figures 6.7 to 6.9. These graphical results are presented only for the cases with a 10% discount rate. The trends displayed for this case are applicable to the other two discount rates.

Distributions of the NPV for both the case where engineering flexibilities are incorporated into the portfolio and the case where they are not incorporated are shown in Figure 6.7 below:

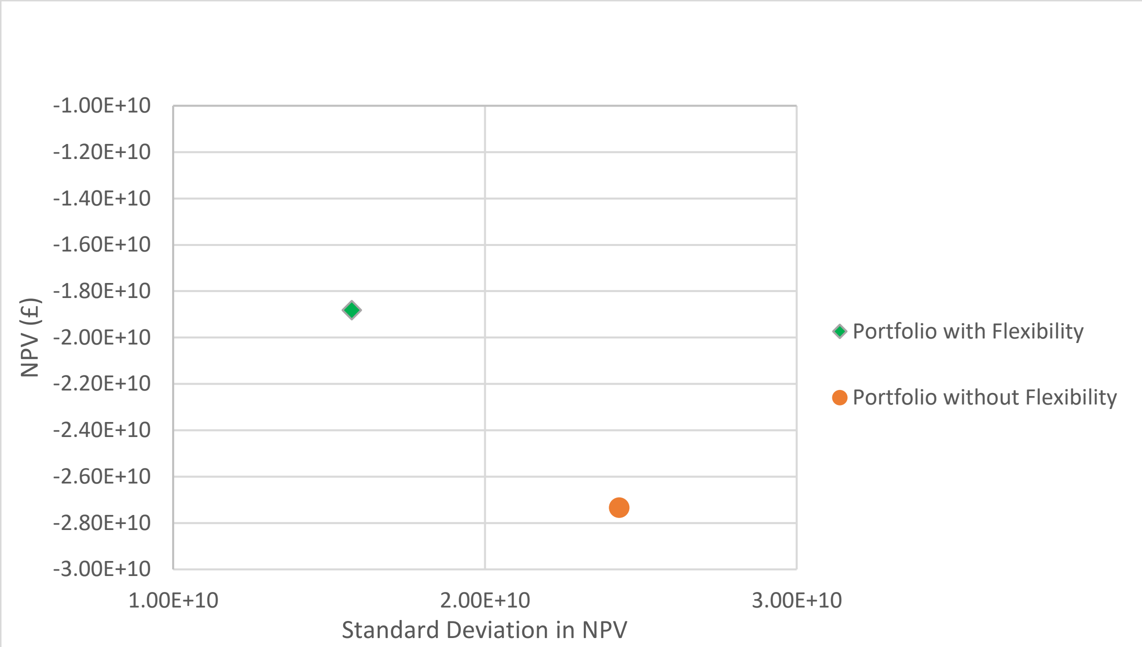
Figure 6.7: Distribution of NPV Values for Portfolios With and Without Flexibilities: 10% Discount Rate



As shown by the figures introduction of the engineering flexibility reduces the divergence of the distribution of NPVs. In particular the left hand “tail” is reduced, thus increasing mean and median values of the distribution. The right-hand tail of the distribution is also reduced meaning that the Value at Gain (95th percentile) is reduced by the introduction of flexibility to the portfolios.

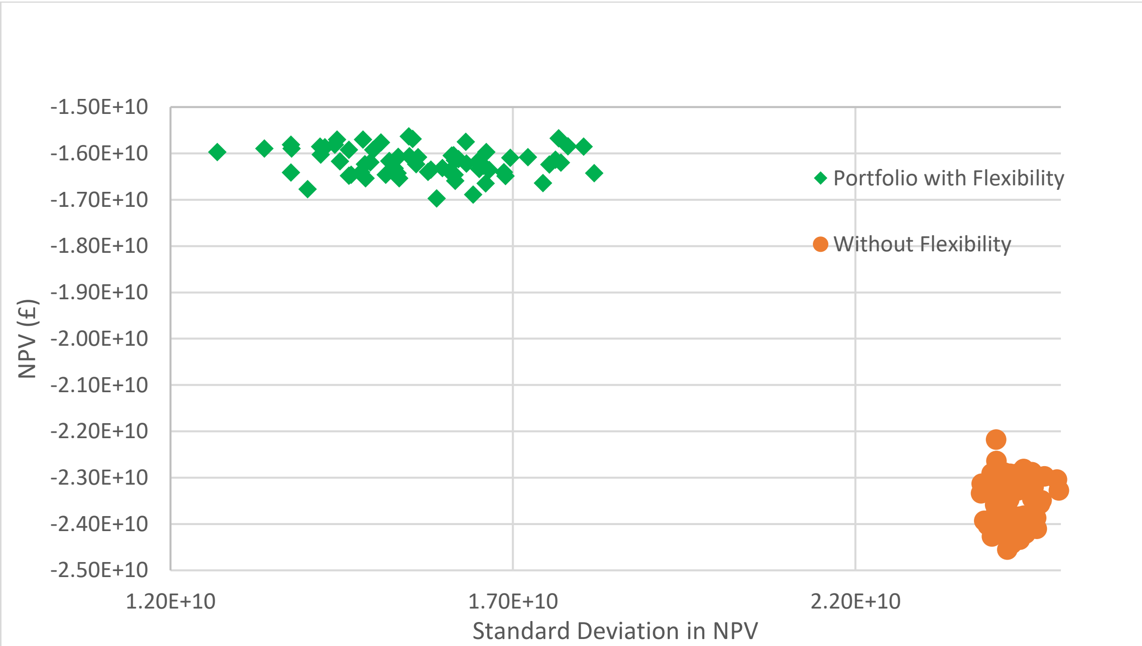
The median values of the NPV for both cases are shown below plotted against their standard deviation confirming the increase in the median value and decrease in the standard distribution as shown above.

Figure 6.8: Net Present Values and Standard Deviations: All Energy and Carbon Price Worlds:10% Discount Rate, All Portfolios.



The values plotted above are the median values for all possible portfolios and therefore take no account of the variability between the 66 different possible portfolios. The distribution of the NPVs and standard deviations of the NPVs for the members of both classes of portfolios are shown in figure 9 below:

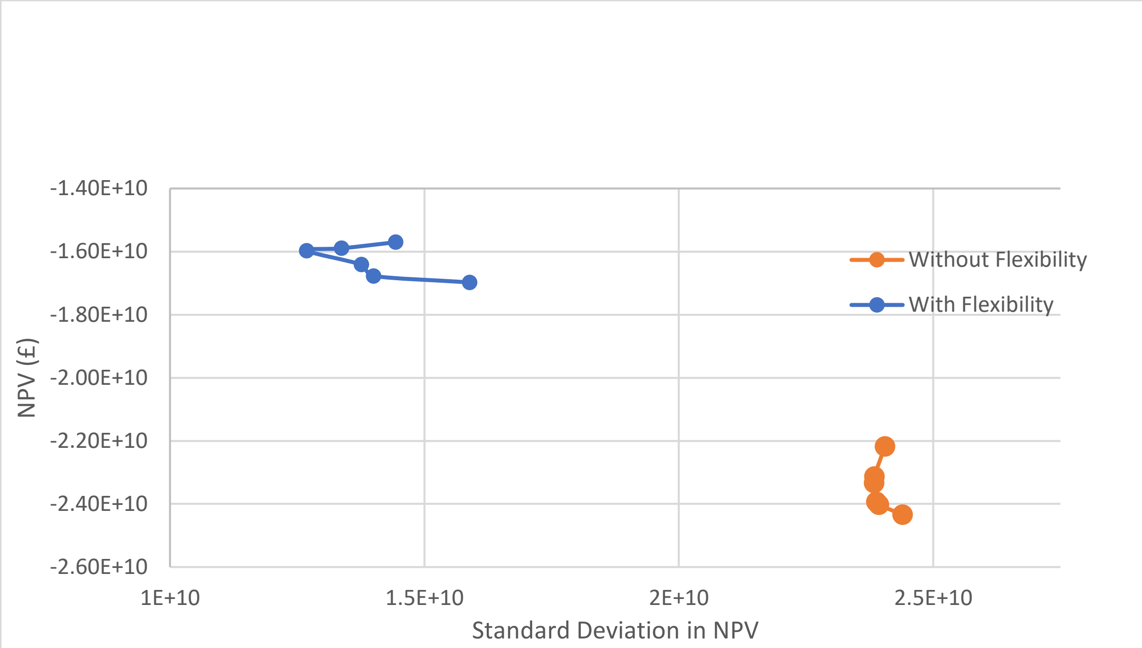
Figure 6.9: Net Present Values and Standard Deviations: All Energy and Carbon Price Worlds: 10 % Discount Rate



Each point in the graph represents the combination of NPV and the standard deviation in NPV for a given portfolio. As can be seen, the inclusion of engineering flexibility / real options increases the NPV for all portfolios when compared to the equivalent portfolio without these. The introduction of flexibility also results in a decrease in the standard deviation of the NPVs.

The efficient frontiers for both cases are shown in Figure 6.10 below.

Figure 6.10: Efficiency Frontier for Portfolios With and Without Flexibility: All Energy and Carbon Price Worlds: 10 % Discount Rate



These are shown in greater detail in figures 6.11 and 6.12 below (note the different scales).

Figure 6.11: Efficiency Frontier for Portfolio With Flexibility: All Energy and Carbon Price Worlds: 10 % Discount Rate

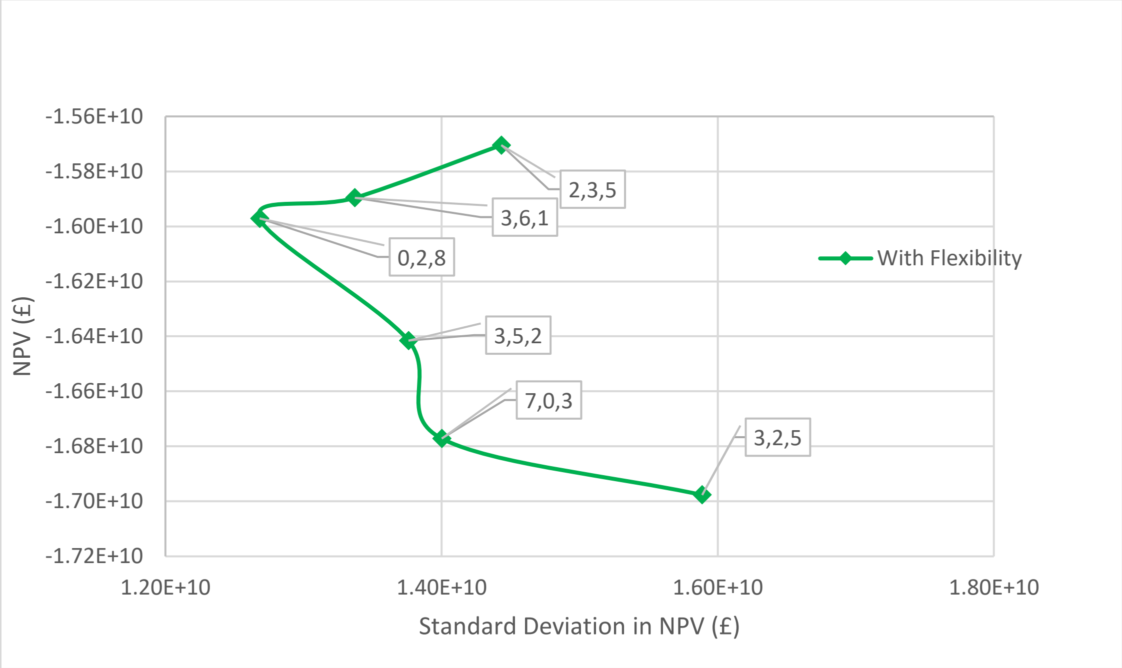
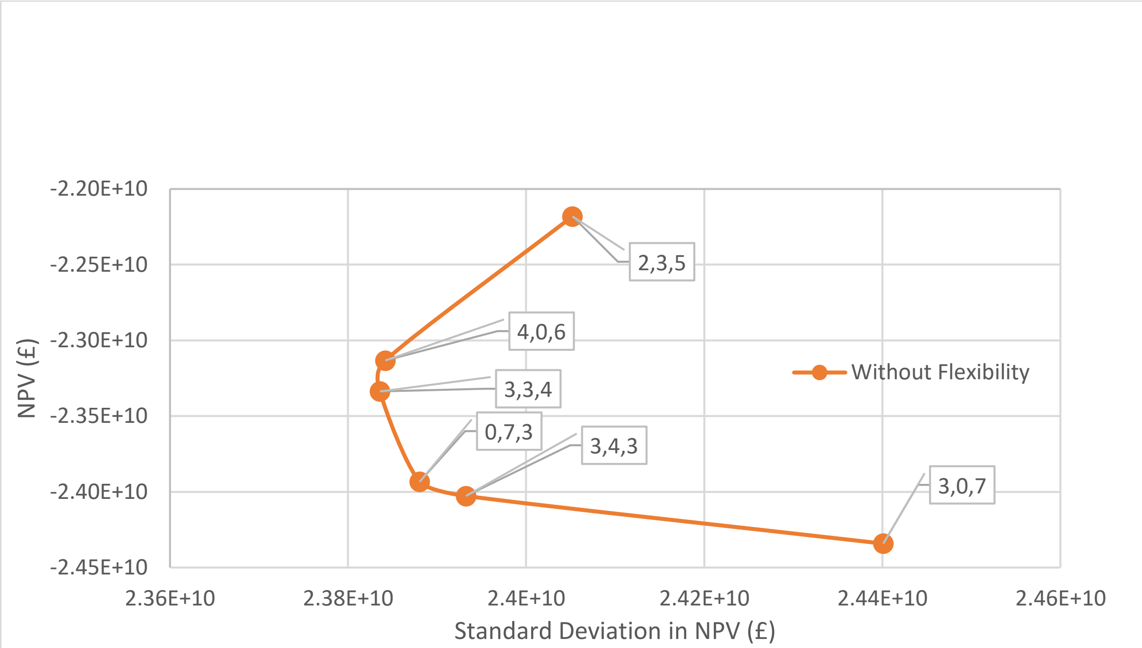


Figure 6.12: Efficiency Frontier for Portfolio Without Flexibility: All Energy and Carbon Price Worlds: 10 % Discount Rate



The labels on the points refer to the number of units of the three different types in the portfolio in the order: electricity generation units, units for hydrogen production and units for sequestration. For example, 3,3,4 is a portfolio composed of three electricity units, three for hydrogen and four for sequestration.

As can be seen there is a range of configurations of those portfolios that lie on the efficient frontiers and the combinations of types of units on the frontier are largely different for the cases with and without flexibility. For both cases the highest NPV is given by a portfolio with 2 electricity generation only plants, 3 with the flexibility to be retrofitted for hydrogen production and 5 with the flexibility to be retrofitted for CO_2 sequestration. There are, however, portfolios which have the lower standard deviations (but with lower NPV values).

As can be seen from Tables 6.1 and 6.2 below the introduction of flexibility increases both the mean and median values of the NPV. The introduction of the flexibilities also reduces the Value at Risk but reduces the Value at Gain reflecting the reduction in the standard deviation of the values.

Table 6.1 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility All Energy and Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-7.22E+10	-1.28E+11	-1.58E+11
Mean	-2.73E+10	-4.08E+10	-4.74E+10
Median	-2.33E+10	-3.38E+10	-3.90E+10
Value at Gain (95th Percentile)	5.83E+09	2.55E+10	3.76E+10
Standard Deviation in NPV	2.43E+10	4.70E+10	5.96E+10

Table 6.2 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: All Energy and Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-3.96E+10	-5.24E+10	-5.73E+10
Mean	-1.88E+10	-2.03E+10	-1.97E+10
Median	-1.62E+10	-1.31E+10	-9.97E+9
Value at Gain (95th Percentile)	-2.79E+09	4.18E+08	3.22E+09
Standard Deviation in NPV	1.57E+10	3.05E+10	3.92E+10

The value of the flexibility is quantified for different parameters in Table 6.3 below. This shows, as indicated above that the flexibility increases all the values with the exception of the Value at Gain. Again, results with greater granularity are presented in the Annex E of the Appendix.

Table 6.3 Value of Incorporating Flexibility (£): All Energy and Carbon Worlds

	Discount Rate		
	10.00%	5.00%	3.50%
Value at Risk (5th Percentile)	3.27E+10	7.57E+10	1.01E+11
Mean	8.53E+09	2.05E+10	2.77E+10
Median	7.14E+09	2.08E+10	2.90E+10
Value at Gain (95th Percentile)	-8.61E+09	-2.51E+10	-3.44E+10

The stochastic nature of some of the input parameters means that the option given by the engineering flexibilities are not exercised in all iterations of the model. Table 6.4 below shows the proportion of cases in which the options are exercised in different conditions.

Table 6.4 Proportion of Cases Where the Options are Exercised.

Energy World	Carbon World	The proportion of Cases Where the Option to Switch to Hydrogen Production is Exercised.	The proportion of Cases Where the Option to Switch to Carbon Sequestration is Exercised.
All	All	4.34%	0.14%
High	High	0.00%	0.10%
Mean	High	38.95%	0.61%
Low	High	91.61%	11.46%
High	Mean	0.00%	0.00%
Mean	Mean	38.85%	0.00%
Low	Mean	91.47%	0.00%
High	Low	0.01%	0.00%
Mean	Low	39.08%	0.00%
Low	Low	91.85%	0.00%

As the table shows, under the conditions used in this analysis, the option to retrofit the unit to produce hydrogen is exercised significantly more often than the option to retrofit for CO_2 sequestration. The option to retrofit for hydrogen production is more frequently made in the circumstances of low electricity prices and only rarely when the price is high. The option to retrofit for sequestration is only exercised in the high carbon credit price scenario and then predominately when the price of electricity is low.

The analyses reported above, in many cases, demonstrate negative NPVs. This contradicts the conclusions of Chapter 4 which demonstrates that there are combinations of electricity prices, discount rates and capital costs which would result in positive NPVs for a fusion SMR supplying electricity to the UK grid. In that analysis, in addition to the electricity price scenarios used here, two additional electricity price scenarios were considered: one, constant price, equal to the strike price agreed for the Hinkley Point C power station currently under construction (National Audit Office, 2017), and one equal to the strike price it is believed that the proposers of the Wylfa C project were seeking (The Financial Times, 2018). It is these higher electricity prices which give rise to the positive NPVs reported in Chapter 4.

The modelling of the portfolio with flexibility has been repeated using these two higher electricity price scenarios[53].

The results of these calculations are given in Table 6.4 below:

Table 6.4: Statistics of the NPV (£M) of the Portfolio with Flexibility for electricity prices equal to Hinkley C and Wylfa C Strike Prices.

		Discount Rate		
		10%	5%	3.5%
Hinkley Point Strike Price	Mean	-1.59E+09	1.63E+10	2.80E+10
	Median	-1.18E+09	1.47E+10	2.53E+10
	5th Percentile	-4.90E+09	4.85E+09	7.45E+09
	95th Percentile	3.32E+08	3.38E+10	5.90E+10
Wylfa C Strike Price	Mean	-6.24E+09	5.49E+09	1.34E+10
	Median	-5.51E+09	4.80E+09	1.20E+10
	5th Percentile	-1.42E+10	2.40E+09	4.63E+09
	95th Percentile	-9.59E+08	1.08E+10	2.71E+10

As can be seen, except for the case of a 10% discount rate, under these price assumptions, the NPVs are positive. It should, however, be noted that in none of the iterations of the model were either of the options exercised as the income from the sale of electricity means that the alternative “products” do not provide a greater income.

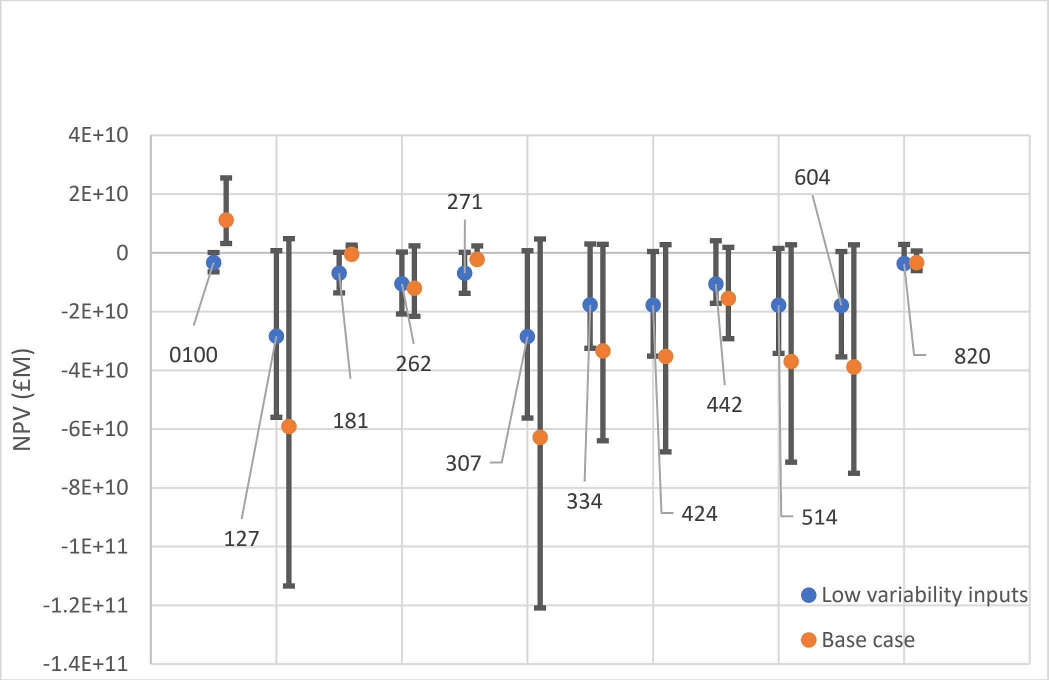
The results show a high degree of uncertainty, i.e., the standard deviations are large. This, it is believed to be a result of the high degree of volatility in the prices of electricity and hydrogen incorporated in the model. If the operator/developer was able to negotiate a fixed price for electricity through a contract for difference or

[53] These prices have been updated to 2020 prices. In Chapter 4, 2018 prices were used.

a similar arrangement, it is likely that the standard deviation in the NPV would be reduced.

To investigate this, a version of the model was constructed in which external sources of uncertainty were removed. The electricity price was set at a constant £55 per MWhr[54], the hydrogen price time series had the random noise term removed and the mean costs for carbon credits and the price of a retrofitted electrolysis plant were used. Some of the results obtained from this variant of the model are shown in Figure 6.13 below. Only a proportion of the portfolios are included for clarity. The labels refer to the composition of the portfolio in the order, electricity generation only, capable of being retrofitted for hydrogen production and capable of being retrofitted for CO_2 sequestration. The error bars represent the range +/- one standard deviation.

Figure 6.13; Ranges of NPVs for Selected Portfolios: Low Variability Input and Base Cases



As can be seen from the figure, the reduction in the variability in the cost inputs leads to a corresponding reduction in the variability in the calculated NPV of the portfolio.

[54] This value was selected so as to ensure that the options were exercised in some of the model iterations.

Chapter Conclusions.

The analysis described above show that if a developer considering the deployment of a fleet of fusion SMRs would be likely to increase the return on their investment if they were to incorporate engineering flexibilities into the fleet to enable them to be retrofitted to be able to produce “products” other than electricity generation. These flexibilities would give the option to adapt the fleet in order to respond to changing market conditions.

The analysis also shows that there are a number of portfolios i.e., combinations of types of plants within the fleet which give rise to different combinations of return and risk.

The results of this analysis are dependent on the values of future costs and prices, which by their nature, cannot be predicted with certainty. If the costs and prices are different from those assumed the value of the flexibilities may well be different.

The approach described above has its limitations. In particular no attempt has been made to correlate any of the input parameters. Also, no account has been taken learning effects on the capital and operating costs of a retrofitted unit for the sequestration of CO_2. If the costs of such a plant reduce over the time period considered it is likely that this option will be exercised in a greater proportion of cases. Consequently, the value of this option will be increased.

In the modelling, no account has been taken of the cost of the biomass feedstock. Conversely, no account has been taken of any income from the sale of the sequestrated carbon as a soil conditioner.

Whilst the modelling can be enhanced, if the necessary data becomes available, it demonstrates that under the conditions considered that the use of engineering flexibilities / real options has the potential to increase the value to the developer of a portfolio of fusion SMR plants designed and constructed to produce different “products”.

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Chapter 7: Conclusions

The thesis proposed two initial questions the research reported here has sought to answer:

- "If small modular fusion reactors prove practical in scientific and engineering terms, will they be practical in commercial terms?"
- "Are there financial techniques and approaches that a developer of a fusion SMR can use to increase the value of their investment?".

The work carried out and reported here has followed a trajectory of increasing complexity. The first three chapters provide some necessary background information. Subsequent chapters have then dealt with the calculation of NPVs and then moved to consider the impact of engineering flexibilities / real options. The final chapter has extended this to include the use of a portfolio approach for the assessment of a fleet of fusion SMRs.

The conclusions of these chapters are outlined below. Consideration has only been given to the financial aspects of fusion commercialisation. No attempt has been made to assess the technical feasibility or whether the timescales suggested by proponents will be achievable. Financial viability will not be achieved without sufficient technological progress which in turn will encourage investment.

The first two chapters of this thesis have outlined the background to the technology of fusion and the other technologies that have been incorporated in the assessments undertaken in this work. They also outline the assessment techniques used. Chapter 3 has reviewed the sources of finance that may be available to the developer of a fusion SMR. It also describes some of the income streams that may be available to the developer.

Fusion SMRs have a number of advantages over other low-carbon sources of energy. Compared to solar and wind energy, if fusion can achieve reliability, it will not suffer from the problem of interrutibility and therefore would not need to be coupled with a storage capability.

Compared to nuclear fission, fusion has the advantage that it does not produce large amounts of radioactive products. This means that the amount of radioactive material available to be released to the environment following any accident is very much reduced. Similarly, the amount of radioactive waste that will need to be stored or disposed of is reduced.

The modular approach is claimed by its proponents to have advantages over the conventional large scale approaches used in fission (as exemplified by the Hinkley Point C project) and fusion (exemplified by the multi-national ITER/DEMO programme). These advantages include the ability to manufacture components in a factory environment and to take advantage of learning effects to reduce costs as a large number of plants are produced.

The first stage of this investigation, as reported in Chapter 4, has considered the case of a fusion SMR supplying electricity to the UK grid. The technique of NPV calculations has been used to investigate the financial viability of the plant. A number of scenarios of discount rates and electricity price were considered. The calculations also considered the First of a Kind (FOAK) plant and a Nth of a Kind (NOAK) plant.

The assessments reported in Chapter 4 showed that there are combinations of discount rates and electricity prices that result in a positive NPV i.e., the developer will obtain a return on their investment. This result holds for both the FOAK and NOAK cases although the range of circumstances in which a positive NPV is obtained is greater for the NOAK case, largely as a result of the lower capital costs. Calculations were also carried out to investigate the extent of the “space” in which the combination of capital costs, electricity prices and discount rates in which a positive NPV is obtained.

The investigations have also shown the value of the NPV depends on the availability of the plant. If unplanned outages occur at a greater frequency than has been assumed in the calculations it may be difficult for a developer to obtain a positive NPV. This produces an uncertain element of risk to a strategy of using a fusion SMR to provide electricity to the UK grid.

Following on from the consideration of the NPV of a fusion SMR the work moved on, as described in Chapter 5, to the consideration of engineering flexibilities / real options. Whilst this consideration has been carried out in the context of a methane steam reformation plant producing hydrogen, the results are relevant to the case of a fusion SMR. This is discussed in Chapter 6. The work in Chapter 5 shows that the NPV approach can be extended to a context where engineering flexibilities / real options are available. The flexibility gives the operator the ability to respond to changes in the environment in which the plant is being operated.

The analysis has shown that the systematic approach of a framework such as that proposed by Cardin (Cardin, 2013) can be used to identify flexibilities that can increase the value of a project to its developer and investors. It can also reduce the risk of a loss being incurred (i.e., the value at risk is reduced).

This approach was then applied to the case of a fleet of fusion SMRs in conjunction with a portfolio approach. This is reported in Chapter 6. In this chapter portfolios have been constructed consisting of fleets of fusion SMR with the capability to produce different products, electricity, hydrogen and CO_2 sequestration. The analysis shows that the different portfolios have different combinations of mean NPV and risk as represented the standard deviation in the NPV. This would allow the developer to select the portfolio which has the NPV and risk which most closely reflects their risk preference. Positive mean NPVs are obtained for all portfolios in the cases where high (“Hinkley” and “Wylfa”) electricity price scenarios are used in conjunction with discount rates of 5% and 3.5%.

This approach has then been extended to include engineering flexibilities / real options into the portfolio approach. Instead of the fleet being comprised of fusion SMRs constructed to be only able to produce one “product” they are constructed[55] to be capable of being retrofitted so that they can produce hydrogen or sequestrate CO_2. This incorporation of flexibility into the portfolio results in increased mean NPVs and reductions in the standard deviations of the NPV. Thus, the value to the developer is increased.

The research in this thesis has therefore shown, in response to the first question posed, that a fusion SMR, if it is technically achievable can, given favourable combinations of capital costs, electricity prices and discount rate can be a viable financial proposition. This assessment relies on the assumption that the availability of the fusion SMR is that which the developers envisage it will be. If a high level of availability is not achieved obtaining a positive NPV may prove difficult.

[55] Except for the variant that is designed only to generate electricity throughout its life.

The use of Engineering Flexibilities / Real Options has the potential to increase the value of an operator's investment. The use of these Engineering Flexibilities / Real Options allows the operator to respond to changes in the environment in which the plant is operated. In the case of the Methane Steam Reformation plant considered in Chapter 5, these are the changes in the prices of natural gas and electricity and the costs associated with the release of CO2 to the atmosphere. By having the engineering flexibilities incorporated in the plants from the design stage, the operator can, depending on the scenario considered, retrofit a carbon capture unit, or to cease operation of a plant fitted at the time of construction. if it appears that making these changes will increase the value of the plant. The work described in Chapter 5 has shown that, in most cases, the availability of the option will increase the mean NPVs. In some cases, the addition of the option will decrease the NPV as the additional cost of constructing the plant so that it can be retrofitted outweigh any increase in value from exercising the option.

The plant considered in Chapter 5 only has one type of flexibility. The work has been extended in Chapter 6 to incorporate a portfolio approach. This approach considered a fleet of fusion SMRs some with the Engineering Flexibility / Real Options to be able to be retrofitted to produce "products" other than electricity for supply to the grid (in this case the production of hydrogen and the sequestration of atmospheric CO_2). The NPVs of different portfolios (containing different mixes of the types of plant) were calculated and compared with the NPVs of similar portfolios without the flexibilities. This analysis has shown that the incorporation of Engineering Flexibilities / Real Options within the portfolio will both increase the mean NPVs and reduce the variability in these NPVs i.e. the efficient frontier is moved upwards and towards the left.

Thus, it has been demonstrated that the adoption of Engineering Flexibilities / Real Options has the potential to increase the value of a developer's investment in a fusion SMR and to also reduce the downside risk. Further, it has been shown that the use of a portfolio approach, in conjunction with these flexibilities, can further increase the value of the investment and reduce the risk.

Limitations of this Work

The calculations and conclusions presented in this thesis, depend on predictions of future costs and prices produced by others. These are subject to both the normal uncertainties associated with such predictions which have been considered, and the impact of “black swan” events (Taleb, 2007). During the course of the studies reported in this thesis two geopolitical events, the covid pandemic and the conflict in Ukraine, have impacted significantly on the prices of energy. This has only been partially considered (in Chapter 5). A future event impacting on costs and prices during the timescales considered in this thesis cannot be ruled out. How such event would impact the financial viability of a fusion SMR cannot be predicted. The war in Ukraine has also refocused attention on the issue of energy security (IEA, 2023). How this increased attention to energy security will impact on the economics of a fusion SMR, which will not rely on external sources of fuel[56] is not known.

As the date as which proponents of fusion SMRs believe that the technology will be achievable gets closer the uncertainties in costs and prices will be reduced. It is possible that updated versions of the assessments will result in different conclusions. Some sensitivity analysis has been carried out in Chapters 3 and 5, but a sensitivity analysis would enhance the work presented in Chapter 6.

The analyses reported in this thesis have concentrated on the financial aspects. No consideration has been given how the engineering systems, the fusion plants, the MSR plants, carbon capture plants and the sequestration plants could be optimised so as to improve the financial performance.

Possible Future Work

Only two alternative technologies have been considered in the application of portfolio theory in conjunction with engineering flexibilities / real options (Chapter 6). As shown in Table 1.2 the IAEA have identified a number of alternative possible uses for the energy produced by a fission power plant (IAEA, 2010), (IAEA, 2013a) and (IAEA, 2013b). These technologies are potentially equally applicable to being used in conjunction with a fusion SMR. Consideration of fusion SMRs with the Engineering Flexibilities / real options to be able to be retrofitted to make use of these technologies in addition to or in place of the technologies considered in Chapter 6 may identify additional value that a developer of a fusion SMR could obtain.

[56] This assumes that the tritium breeding capability will function as the developers believe it will and the plant will be self sufficient in tritium.

The consideration of the fusion SMR in this thesis has been limited in that it has considered the fusion SMR as a “black box” providing energy. No attempt has been made to consider whether there are factors in the design or operation of the SMRs, or the technologies used in conjunction with the reactor, that could be amended to optimise the financial performance. Wilson and colleagues (Wilson et al., 2020) have investigated the linking of an engineering model of a fission SMR operated in conjunction with an air storage plant with a financial model. The application of such an approach, the integration of engineering model with a financial model may provide useful insights to the developer of fusion SMRs.

Similarly, no consideration has been given as to the design and operation of the MSR and CCS plant considered in Chapter 5. It would be a useful exercise to combine the financial models described there with an engineering model of these plants.

As mentioned above, the amount of sensitivity analysis carried out as part of the work reported in this thesis is limited and has largely been confined to Chapter 5. A more extensive sensitivity analysis, that considers aspects of the plant design (both of the fusion plant and of the other technologies considered in this thesis), has the potential to reveal areas in which a developer could focus their attention in order to improve their financial return.

References Chapter 7

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Appendix: Supplementary Information

Annex A: Other Parameters Used the Model in Chapter 5:

Table A1: Carbon Price Projections Used.

	Carbon Price Prediction		
	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

	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 Detailed NPV Results For Chapter 5

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

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£328.11	£704.48
Energy World	**Carbon World**		
High	High	-£62.23	£406.52
High	Base	-£54.93	£417.99
High	Low	-£55.50	£411.69
Base	High	£296.38	£634.08
Base	Base	£308.55	£638.07
Base	Low	£295.89	£629.43
Low	High	£744.82	£961.57
Low	Base	£747.35	£958.61
Low	Low	£746.83	£960.15

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

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£247.34	£549.78
Energy World	**Carbon World**		
High	High	-£76.87	£296.16
High	Base	-£91.58	£298.82
High	Low	-£64.13	£304.13
Base	High	£234.40	£492.77
Base	Base	£226.75	£496.41
Base	Low	£231.69	£496.32
Low	High	£597.42	£759.26
Low	Base	£591.16	£766.34
Low	Low	£599.76	£768.16

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

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£105.03	£249.61
Energy World	**Carbon World**		
High	High	-£75.03	£96.23
High	Base	-£76.15	£97.61
High	Low	-£82.97	£94.45
Base	High	£96.69	£224.73
se	Base	£104.12	£226.67
Base	Low	£107.71	£229.13
Low	High	£290.21	£375.90
Low	Base	£286.57	£368.64
Low	Low	£290.69	£369.88

Table B4 NPV With No CCS 3.5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£174.07	£128.93
Energy World	**Carbon World**		
High	High	-£937.86	-£479.27
High	Base	-£496.57	-£38.13
High	Low	-£222.25	£226.01
Base	High	-£583.53	-£269.13
Base	Base	-£139.75	£173.99
Base	Low	£135.10	£447.31
Low	High	-£152.93	£60.79
Low	Base	£295.07	£500.86
Low	Low	£575.20	£772.08

Table B5 NPV With No CCS 5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£128.61	£104.31
Energy World	Carbon World		
High	High	-£745.41	-£395.93
High	Base	-£411.29	-£57.79
High	Low	-£181.85	£163.44
Base	High	-£439.17	-£204.75
Base	Base	-£105.51	£136.65
Base	Low	£132.79	£356.82
Low	High	-£106.79	£54.69
Low	Base	£241.22	£406.99
Low	Low	£463.99	£623.00

Table B6 NPV With No CCS 10 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£69.91	£41.15
Energy World	**Carbon World**		
High	High	-£396.10	-£241.97
High	Base	-£236.45	-£65.78
High	Low	-£104.70	£44.27
Base	High	-£222.54	-£115.75
Base	Base	-£52.87	£51.04
Base	Low	£69.80	£173.47
Low	High	-£40.88	£30.10
Low	Base	£125.58	£196.45
Low	Low	£236.64	£307.59

Table B7 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 B8 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 B9 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 B10 NPVs With Option to Stop CCS 3.5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£62.97	£474.44
Energy World	**Carbon World**		
High	High	-£344.92	£192.73
High	Base	-£365.76	£170.02
High	Low	-£336.88	£186.81
Base	High	£37.48	£410.59
Base	Base	£22.32	£411.16
Base	Low	£46.37	£405.02
Low	High	£497.17	£733.70
Low	Base	£513.10	£740.30
Low	Low	£510.05	£742.13

TableB11 NPVs With Option to Stop CCS 5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£10.54	£328.26
Energy World	**Carbon World**		
High	High	-£340.24	£74.97
High	Base	-£346.68	£70.97
High	Low	-£318.19	£76.38
Base	High	£3.59	£277.51
Base	Base	-£0.72	£276.66
Base	Low	-£3.15	£274.90
Low	High	£377.84	£550.70
Low	Base	£364.53	£545.63
Low	Low	£379.07	£545.62

Table B12 NPVs With Option to Stop CCS 10 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£94.53	£54.13
Energy World	**Carbon World**		
High	High	-£276.42	-£89.87
High	Base	-£282.15	-£88.92
High	Low	-£270.76	-£87.18
Base	High	-£90.50	£33.49
Base	Base	-£94.13	£30.50
Base	Low	-£93.80	£29.63
Low	High	£83.34	£167.95
Low	Base	£89.73	£171.93
Low	Low	£87.95	£171.62

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 NPV With No CCS 3.5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£124.32	£72.35
Energy World	**Carbon World**		
High	High	-£683.14	-£332.75
Base	Base	-£85.32	£91.99
Low	Low	£407.65	£405.20

Table B5a NPV With No CCS 5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£134.52	£114.04
Energy World	**Carbon World**		
High	High	-£758.52	-£400.95
Base	Base	-£100.28	£140.67
Low	Low	£466.95	£625.59

Table B6a NPV With No CCS 10 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£73.67	£43.34
Energy World	**Carbon World**		
High	High	-£399.30	-£239.06
Base	Base	-£54.87	£50.49
Low	Low	£235.64	£305.91

Table B7a 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 B8a 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

Table B9a 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

Table B10a NPVs With Option to Stop CCS 3.5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£61.22	£472.99
Energy World	**Carbon World**		
High	High	-£335.15	£182.79
Base	Base	-£39.32	£406.44
Low	Low	£502.97	£733.91

Table B11a NPVs With Option to Stop CCS 5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£9.89	£328.62
Energy World	**Carbon World**		
High	High	-£345.29	£78.48
Base	Base	-£0.34	£275.66
Low	Low	£377.10	£548.26

Table B12a NPVs With Option to Stop CCS 10 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£89.15	£53.91
Energy World	**Carbon World**		
High	High	-£280.02	-£99.51
Base	Base	-£88.55	£28.67
Low	Low	£104.25	£179.75

Annex C: Detailed Value of Options Calculated in Chapter 5

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		£647.40	£623.28
Energy World	Carbon World		
High	High	£781.09	£707.94
High	Base	£706.18	£655.71
High	Low	£627.78	£614.45
Base	High	£671.58	£666.48
Base	Base	£651.49	£635.32
Base	Low	£605.20	£586.53
Low	High	£627.92	£617.19
Low	Base	£585.22	£571.57
Low	Low	£558.07	£542.49

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		£529.21	£527.39
Energy World	Carbon World		
High	High	£590.17	£570.19
High	Base	£543.44	£546.08
High	Low	£554.90	£533.61
Base	High	£560.86	£559.46
Base	Base	£534.05	£536.43
Base	Low	£499.85	£498.46
Low	High	£562.41	£556.28
Low	Base	£536.54	£529.81
Low	Low	£516.63	£510.96

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		£334.35	£337.18
Energy World	Carbon World		
High	High	£368.26	£370.98
High	Base	£356.17	£349.39
High	Low	£336.55	£345.56
Base	High	£337.45	£348.30
Base	Base	£329.92	£337.47
Base	Low	£326.70	£329.50
Low	High	£331.16	£334.75
Low	Base	£307.59	£314.71
Low	Low	£300.09	£302.69

Table C4: Value of option to stop CCS compared to no CCS throughout 3.5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£237.04	£345.51
Energy World	Carbon World		
High	High	£592.94	£672.00
High	Base	£130.81	£208.15
High	Low	-£114.63	-£39.20
Base	High	£621.00	£679.72
Base	Base	£162.07	£237.17
Base	Low	-£88.73	-£42.29
Low	High	£650.10	£672.91
Low	Base	£218.03	£239.44
Low	Low	-£65.15	-£29.95

Table C5: Value of option to stop CCS compared to no CCS throughout 5 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£139.15	£223.95
Energy World	**Carbon World**		
High	High	£405.17	£470.89
High	Base	£64.61	£128.76
High	Low	-£136.33	-£87.06
Base	High	£442.76	£482.26
Base	Base	£104.80	£140.01
Base	Low	-£135.93	-£81.92
Low	High	£484.64	£496.00
Low	Base	£123.31	£138.64
Low	Low	-£84.92	-£77.38

Table C6: Value of option to stop CCS compared to no CCS throughout 10 % Discount Rate

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£24.61	-£12.99
Energy World	**Carbon World**		
High	High	£119.67	£119.67
High	Base	-£45.69	-£45.69
High	Low	-£166.06	-£166.06
Base	High	£132.05	£132.05
Base	Base	-£41.26	-£41.26
Base	Low	-£163.60	-£163.60
Low	High	£124.22	£124.22
Low	Base	-£35.85	-£35.85
Low	Low	-£148.69	-£148.69

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

Table C4a: Value of option to stop CCS compared to no CCS throughout 3.5 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£185.54	£400.64
Energy World	**Carbon World**		
High	High	£329.99	£515.54
Base	Base	£124.64	£314.46
Low	Low	£95.32	£328.71

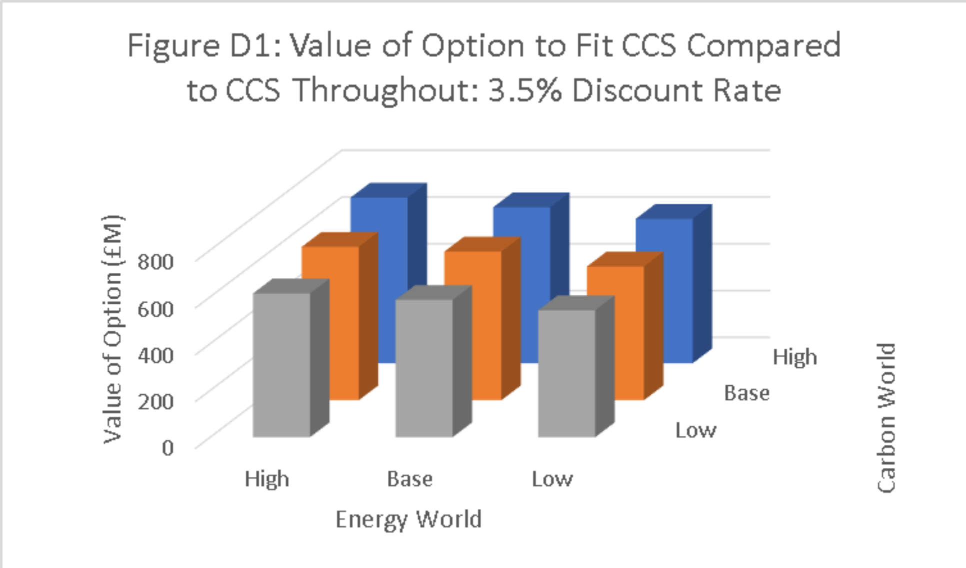
Table C5a: Value of option to stop CCS compared to no CCS throughout 5 % Discount Rate Correlated

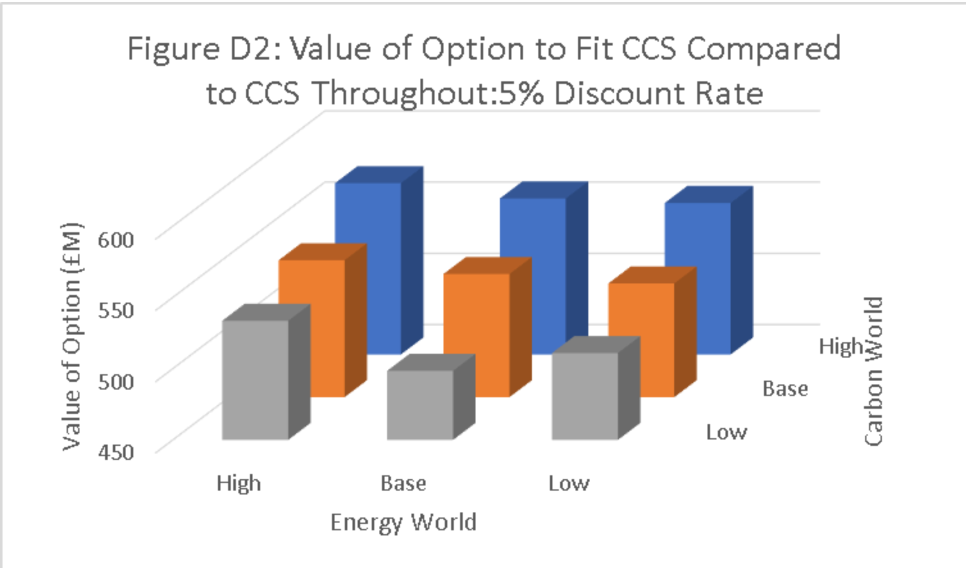
		Mean NPV (£M)	Median NPV (£M)
All Scenarios		£144.41	£214.59
Energy World	**Carbon World**		
High	High	£413.23	£479.43
Base	Base	£99.94	£134.99
Low	Low	-£89.86	-£77.32

Table 5.C6a: Value of option to stop CCS compared to no CCS throughout 10 % Discount Rate Correlated

		Mean NPV (£M)	Median NPV (£M)
All Scenarios		-£15.48	£10.58
Energy World	**Carbon World**		
High	High	£119.28	£139.55
Base	Base	-£33.69	-£21.82
Low	Low	-£131.39	-£126.16

Annex D: Additional Graphs for Chapter 5





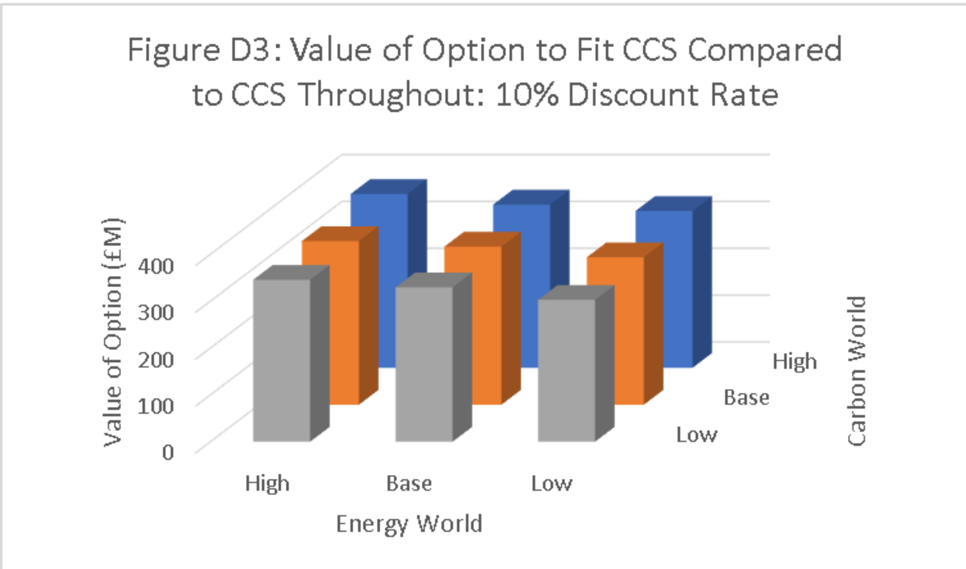


Figure D4: Value of Option to Stop CCS Compared to no CCS: 3.5% Discount Rate

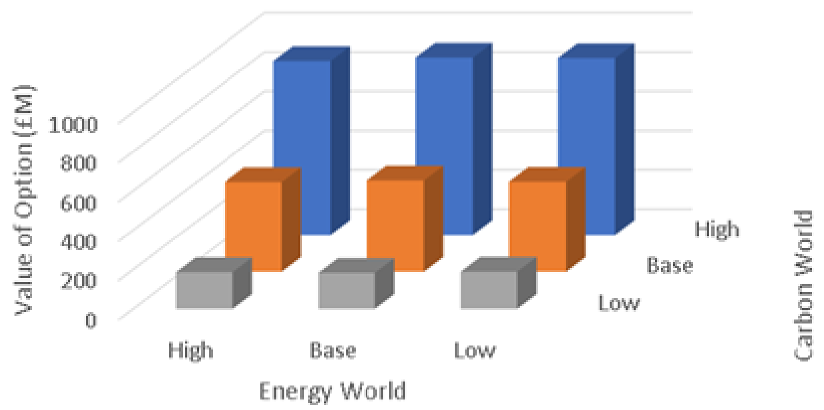


Figure D5: Value of Option to Stop CCS Compared to no CCS: 5% Discount Rate

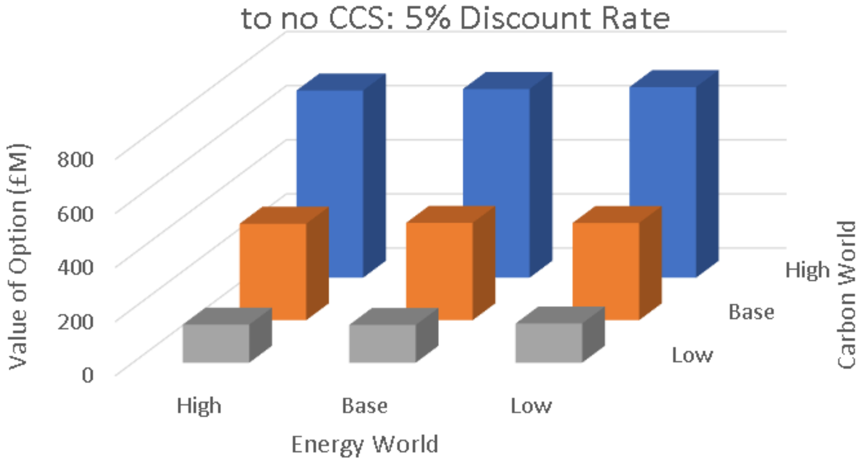
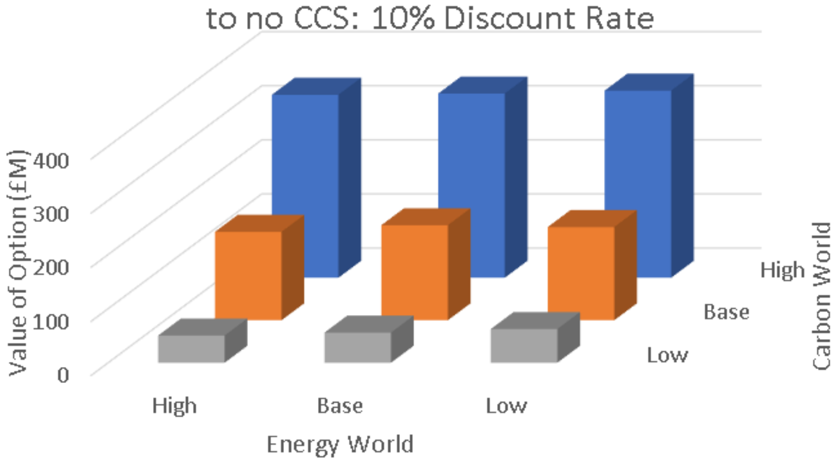


Figure D6: Value of Option to Stop CCS Compared to no CCS: 10% Discount Rate



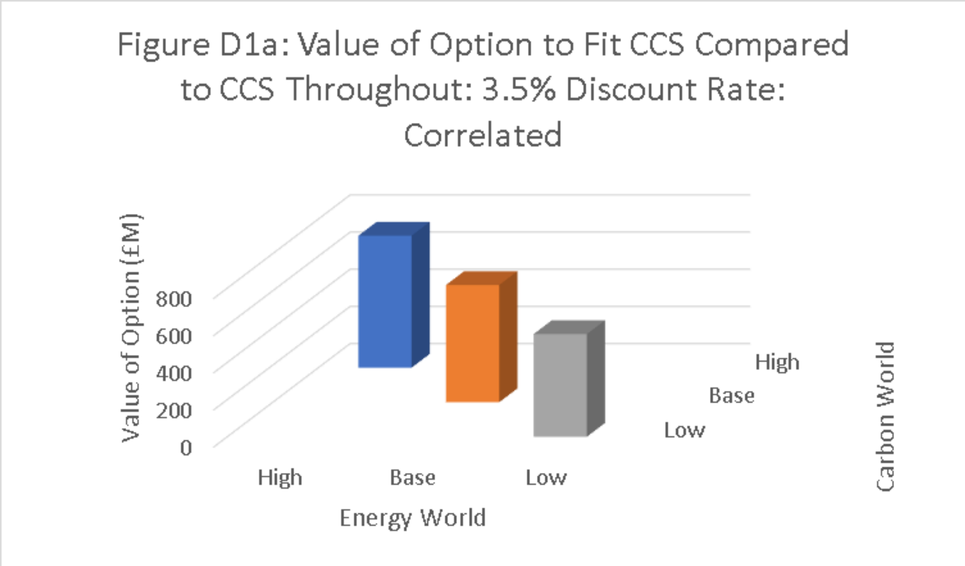


Figure D1a: Value of Option to Fit CCS Compared to CCS Throughout: 3.5% Discount Rate: Correlated
Value of Option (£M)
800
600
400
200
0
High
Base
Low
Energy World
High
Base
Low
Carbon World

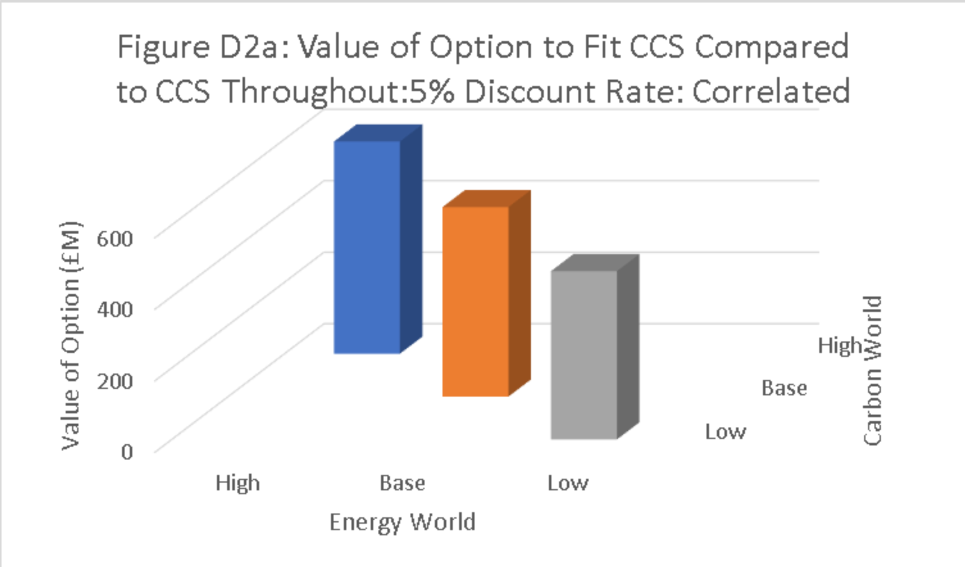


Figure D2a: Value of Option to Fit CCS Compared to CCS Throughout:5% Discount Rate: Correlated
Value of Option (£M)
600
400
200
0
High
Base
Low
Energy World
High
Base
Low
Carbon World

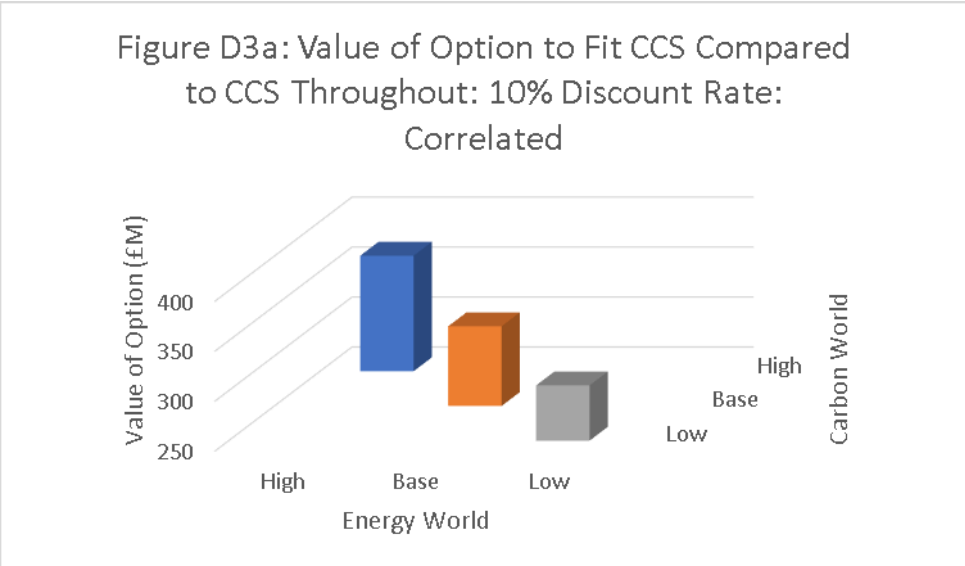


Figure D3a: Value of Option to Fit CCS Compared to CCS Throughout: 10% Discount Rate: Correlated
Value of Option (£M)
400
350
300
250
High
Base
Low
Energy World
High
Base
Low
Carbon World

Fig. D4a: Value of Option to Stop CCS Compared to No CCS Throughout: 3.5% Discount Rate: Correlated

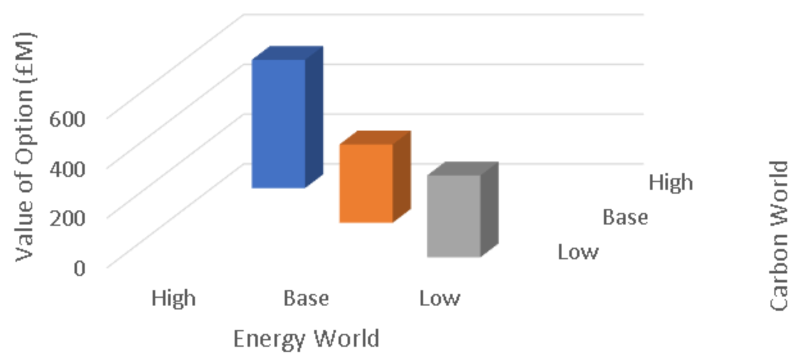
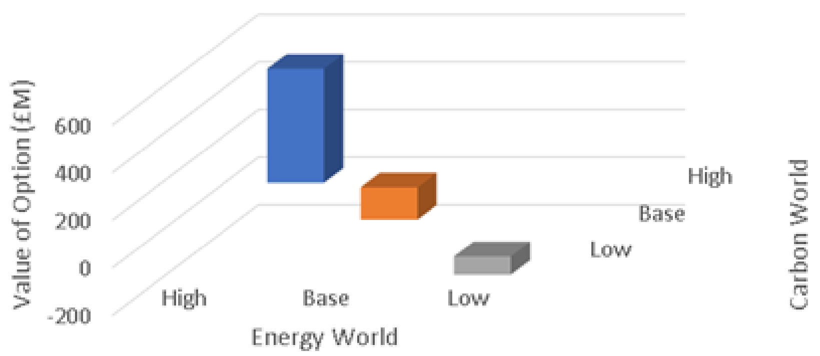


Figure D5a: Value of Option to Stop CCS Compared to No CCS Throughout: 5% Discount Rate: Correalted



Annex E: Additional Results for Chapter 6

Table E1 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility High Energy and Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-6.38E+10	-1.08E+11	-1.31E+11
Mean	-2.56E+10	-3.62E+10	-4.10E+10
Median	-2.14E+10	-3.02E+10	-3.40E+10
Value at Gain (95th Percentile)	3.30E+09	2.00E+10	3.03E+10
Standard Deviation in NPV	2.13E+10	3.99E+10	5.01E+10

Table E2 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: High Energy and Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-2.43E+10	-1.73E+10	-1.18E+10
Mean	-1.11E+10	-5.93E+09	-1.88E+09
Median	-9.98E+09	-4.57E+09	-5.73E+08
Value at Gain (95th Percentile)	-2.23E+09	8.60E+08	3.61E+09
Standard Deviation in NPV	7.05E+09	5.84E+09	5.01E+09

Table E3 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Mean Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-6.37E+10	-1.08E+11	-1.31E+11
Mean	-2.32E+10	-3.14E+10	-3.49E+10
Median	-1.98E+10	-2.67E+10	-2.80E+10
Value at Gain (95th Percentile)	8.42E+09	3.03E+10	4.37E+10
Standard Deviation in NPV	2.24E+10	4.22E+10	5.31E+10

Table E4 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Mean Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-3.45E+10	-3.77E+10	-3.68E+10
Mean	-1.68E+10	-1.68E+10	-1.56E+10
Median	-1.38E+10	-1.20E+10	-9.66E+09
Value at Gain (95th Percentile)	-3.31E+09	8.56E+08	6.86E+09
Standard Deviation in NPV	1.47E+10	2.91E+10	3.76E+10

Table E5 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Low Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-6.36E+10	-1.07E+11	-1.30E+11
Mean	-2.42E+10	-3.34E+10	-3.74E+10
Median	-2.09E+10	-2.82E+10	-3.16E+10
Value at Gain (95th Percentile)	6.06E+09	2.55E+10	3.74E+10
Standard Deviation in NPV	2.18E+10	4.10E+10	5.15E+10

Table E6 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Low Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-4.37E+10	-5.88E+10	-6.53E+10
Mean	-2.90E+10	-3.92E+10	-4.32E+10
Median	-2.95E+10	-3.84E+10	-4.15E+10
Value at Gain (95th Percentile)	-7.88E+09	-8.03E+09	-7.86E+09
Standard Deviation in NPV	1.81E+10	3.79E+10	4.96E+10

Table E7 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Mean Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-7.09E+10	-1.25E+11	-1.54E+11
Mean	-2.62E+10	-3.87E+10	-4.47E+10
Median	-2.28E+10	-3.22E+10	-3.74E+10
Value at Gain (95th Percentile)	8.83E+09	3.07E+10	4.39E+10
Standard Deviation in NPV	2.49E+10	4.81E+10	6.09E+10

Table E8 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Mean Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-3.44E+10	-3.76E+10	-3.65E+10
Mean	-1.68E+10	-1.68E+10	-1.55E+10
Median	-1.39E+10	-1.22E+10	-9.90E+09
Value at Gain (95th Percentile)	-3.32E+09	6.91E+08	6.73E+09
Standard Deviation in NPV	1.46E+10	2.86E+10	3.70E+10

Table E9 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Mean Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-7.09E+10	-1.25E+11	-1.54E+11
Mean	-2.62E+10	-3.87E+10	-4.47E+10
Median	-2.28E+10	-3.22E+10	-3.74E+10
Value at Gain (95th Percentile)	8.83E+09	3.07E+10	4.39E+10
Standard Deviation in NPV	2.49E+10	4.81E+10	6.09E+10

Table E10 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Mean Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-3.44E+10	-3.76E+10	-3.65E+10
Mean	-1.68E+10	-1.68E+10	-1.55E+10
Median	-1.39E+10	-1.22E+10	-9.90E+09
Value at Gain (95th Percentile)	-3.32E+09	6.91E+08	6.73E+09
Standard Deviation in NPV	1.46E+10	2.86E+10	3.70E+10

Table E11 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Low Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-7.10E+10	-1.25E+11	-1.55E+11
Mean	-2.76E+10	-4.13E+10	-4.81E+10
Median	-2.32E+10	-3.66E+10	-4.13E+10
Value at Gain (95th Percentile)	6.14E+09	2.56E+10	3.74E+10
Standard Deviation in NPV	2.43E+10	4.69E+10	5.94E+10

Table E12 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Low Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-4.24E+10	-5.60E+10	-6.12E+10
Mean	-2.86E+10	-3.81E+10	-4.17E+10
Median	-2.91E+10	-3.77E+10	-4.07E+10
Value at Gain (95th Percentile)	-7.92E+09	-8.06E+09	-7.89E+09
Standard Deviation in NPV	1.84E+10	3.90E+10	5.11E+10

Table E13 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility High Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-6.38E+10	-1.08E+11	-1.31E+11
Mean	-2.56E+10	-3.62E+10	-4.10E+10
Median	-2.14E+10	-3.02E+10	-3.40E+10
Value at Gain (95th Percentile)	3.30E+09	2.00E+10	3.03E+10
Standard Deviation in NPV	2.13E+10	3.99E+10	5.01E+10

Table E14 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: High Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-2.43E+10	-1.74E+10	-1.16E+10
Mean	-1.11E+10	-5.91E+09	-1.85E+09
Median	-9.95E+09	-4.59E+09	-5.56E+08
Value at Gain (95th Percentile)	-2.23E+09	8.67E+08	3.69E+09
Standard Deviation in NPV	7.07E+09	5.91E+09	5.14E+09

Table E15 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Mean Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-7.68E+10	-1.40E+11	-1.74E+11
Mean	-2.88E+10	-4.49E+10	-5.31E+10
Median	-2.44E+10	-4.03E+10	-4.64E+10
Value at Gain (95th Percentile)	9.11E+09	3.14E+10	4.48E+10
Standard Deviation in NPV	2.69E+10	5.29E+10	6.74E+10

Table E16 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Mean Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-3.42E+10	-3.74E+10	-3.64E+10
Mean	-1.66E+10	-1.65E+10	-1.52E+10
Median	-1.38E+10	-1.20E+10	-9.76E+09
Value at Gain (95th Percentile)	-3.32E+09	1.00E+09	6.96E+09
Standard Deviation in NPV	1.41E+10	2.75E+10	3.54E+10

Table E17 Parameters of the Distribution of the NPV (£): Portfolios without Flexibility Low Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-7.68E+10	-1.40E+11	-1.74E+11
Mean	-3.03E+10	-4.79E+10	-5.69E+10
Median	-2.57E+10	-4.09E+10	-4.98E+10
Value at Gain (95th Percentile)	6.09E+09	2.54E+10	3.72E+10
Standard Deviation in NPV	2.63E+10	5.16E+10	6.58E+10

Table E18 Parameters of the Distribution of the NPV (£): Portfolios with Flexibility: Low Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.50%
Value at Risk (5th Percentile)	-4.25E+10	-5.59E+10	-6.11E+10
Mean	-2.85E+10	-3.78E+10	-4.13E+10
Median	-2.91E+10	-3.78E+10	-4.08E+10
Value at Gain (95th Percentile)	-7.94E+09	-8.05E+09	-7.88E+09
Standard Deviation in NPV	1.72E+10	3.57E+10	4.67E+10

Table E19 Value of Incorporating Flexibility (£): High Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	3.95E+10	9.05E+10	1.19E+11
Mean	1.45E+10	3.02E+10	3.91E+10
Median	1.14E+10	2.56E+10	3.34E+10
Value at Gain (95th Percentile)	-5.53E+09	-1.91E+10	-2.67E+10

Table E20 Value of Incorporating Flexibility (£): Mean Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	2.92E+10	6.99E+10	9.37E+10
Mean	6.45E+09	1.46E+10	1.94E+10
Median	6.04E+09	1.48E+10	1.83E+10
Value at Gain (95th Percentile)	-1.17E+10	-2.94E+10	-3.69E+10

Table E21 Value of Incorporating Flexibility (£): Low Energy and High Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	1.99E+10	4.86E+10	6.51E+10
Mean	-4.83E+09	-5.81E+09	-5.77E+09
Median	-8.55E+09	-1.02E+10	-9.88E+09
Value at Gain (95th Percentile)	-1.39E+10	-3.35E+10	-4.52E+10

Table E22 Value of Incorporating Flexibility (£): High Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	4.64E+10	1.08E+11	1.42E+11
Mean	1.78E+10	3.79E+10	4.94E+10
Median	1.49E+10	3.26E+10	4.41E+10
Value at Gain (95th Percentile)	-5.57E+09	-1.91E+10	-2.66E+10

Table E23 Value of Incorporating Flexibility (£): All Energy and Carbon Worlds

	Discount Rate		
	10.00%	5.00%	3.50%
Value at Risk (5th Percentile)	3.27E+10	7.57E+10	1.01E+11
Mean	8.53E+09	2.05E+10	2.77E+10
Median	7.14E+09	2.08E+10	2.90E+10
Value at Gain (95th Percentile)	-8.61E+09	-2.51E+10	-3.44E+10

Table E24 Value of Incorporating Flexibility (£): High Energy and All Carbon Worlds

	Discount Rate		
	10.00%	5.00%	3.50%
Value at Risk (5th Percentile)	4.71E+10	1.08E+11	1.43E+11
Mean	1.75E+10	3.73E+10	4.86E+10
Median	1.45E+10	3.21E+10	4.12E+10
Value at Gain (95th Percentile)	-5.53E+09	-1.90E+10	-2.65E+10

Table E25 Value of Incorporating Flexibility (£): Low Energy and All Carbon Worlds

	Discount Rate		
	10.00%	5.00%	3.50%
Value at Risk (5th Percentile)	3.02E+10	7.32E+10	9.77E+10
Mean	-1.32E+09	2.54E+09	5.46E+09
Median	-6.16E+09	-4.56E+09	-2.18E+09
Value at Gain (95th Percentile)	-1.40E+10	-3.35E+10	-4.52E+10

Table E26 Value of Incorporating Flexibility (£): All Energy and High Carbon Worlds

	Discount Rate		
	10.00%	5.00%	3.50%
Value at Risk (5th Percentile)	2.38E+10	5.44E+10	7.24E+10
Mean	5.38E+09	1.30E+10	1.75E+10
Median	4.85E+09	1.53E+10	2.18E+10
Value at Gain (95th Percentile)	-8.66E+09	-2.52E+10	-3.46E+10

Table E27 Value of Incorporating Flexibility (£): All Energy and High Carbon Worlds

	Discount Rate		
	10.00%	5.00%	3.50%
Value at Risk (5th Percentile)	3.74E+10	8.73E+10	1.17E+11
Mean	1.15E+10	2.76E+10	3.72E+10
Median	9.77E+09	2.79E+10	3.89E+10
Value at Gain (95th Percentile)	-8.59E+09	-5.16E+10	-6.58E+10

Table E28 Value of Incorporating Flexibility (£): Mean Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	3.64E+10	8.74E+10	1.18E+11
Mean	9.43E+09	2.19E+10	2.92E+10
Median	8.88E+09	2.00E+10	2.75E+10
Value at Gain (95th Percentile)	-1.22E+10	-3.00E+10	-3.71E+10

Table E29 Value of Incorporating Flexibility (£): Low Energy and Mean Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	2.86E+10	6.93E+10	9.34E+10
Mean	-1.00E+09	3.26E+09	6.41E+09
Median	-5.92E+09	-1.10E+09	5.62E+08
Value at Gain (95th Percentile)	-1.41E+10	-3.36E+10	-4.53E+10

Table E30 Value of Incorporating Flexibility (£): High Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	3.96E+10	9.05E+10	1.19E+11
Mean	1.45E+10	3.02E+10	3.91E+10
Median	1.14E+10	2.56E+10	3.35E+10
Value at Gain (95th Percentile)	-5.52E+09	-1.91E+10	-2.66E+10

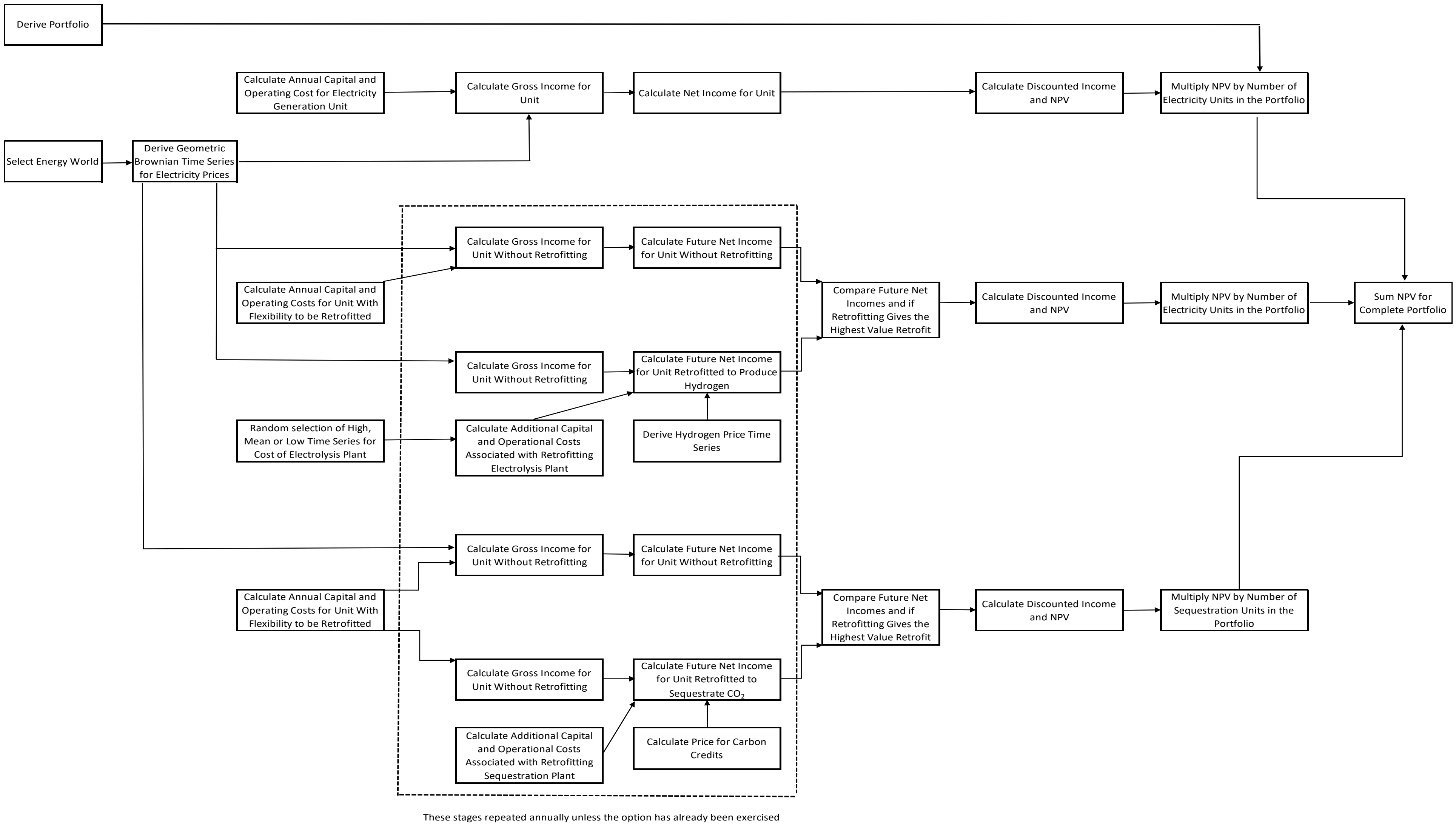
Table E31 Value of Incorporating Flexibility (£): Mean Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
5th Percentile	4.26E+10	1.02E+11	1.37E+11
Mean	1.22E+10	2.83E+10	3.79E+10
Median	1.06E+10	2.83E+10	3.67E+10
95th percentile	-1.24E+10	-3.04E+10	-3.78E+10

Table E32 Value of Incorporating Flexibility (£): Low Energy and Low Carbon Worlds

	Discount Rate		
	10%	5%	3.5%
Value at Risk (5th Percentile)	3.44E+10	8.36E+10	1.13E+11
Mean	1.83E+09	1.01E+10	1.57E+10
Median	-3.43E+09	3.07E+09	9.01E+09
Value at Gain (95th Percentile)	-1.40E+10	-3.35E+10	-4.50E+10

Annex F: Flow Chart of the Model Used in Chapter 6.


Derive Portfolio
Calculate Annual Capital and Operating Cost for Electricity Generation Unit
Calculate Gross Income for Unit
Calculate Net Income for Unit
Calculate Discounted Income and NPV
Multiply NPV by Number of Electricity Units in the Portfolio
Select Energy World
Derive Geometric Brownian Time Series for Electricity Prices
Calculate Gross Income for Unit Without Retrofitting
Calculate Future Net Income for Unit Without Retrofitting
Calculate Annual Capital and Operating Costs for Unit With Flexibility to be Retrofitted
Compare Future Net Incomes and if Retrofitting Gives the Highest Value Retrofit
Calculate Discounted Income and NPV
Multiply NPV by Number of Electricity Units in the Portfolio
Sum NPV for Complete Portfolio
Calculate Gross Income for Unit Without Retrofitting
Calculate Future Net Income for Unit Retrofitted to Produce Hydrogen
Random selection of High, Mean or Low Time Series for Cost of Electrolysis Plant
Calculate Additional Capital and Operational Costs Associated with Retrofitting Electrolysis Plant
Derive Hydrogen Price Time Series
Calculate Gross Income for Unit Without Retrofitting
Calculate Future Net Income for Unit Without Retrofitting
Calculate Annual Capital and Operating Costs for Unit With Flexibility to be Retrofitted
Compare Future Net Incomes and if Retrofitting Gives the Highest Value Retrofit
Calculate Discounted Income and NPV
Multiply NPV by Number of Sequestration Units in the Portfolio
Calculate Gross Income for Unit Without Retrofitting
Calculate Future Net Income for Unit Retrofitted to Sequestrate CO_2
Calculate Additional Capital and Operational Costs Associated with Retrofitting Sequestration Plant
Calculate Price for Carbon Credits
These stages repeated annually unless the option has already been exercised

Annex G: Data used in the Model in Chapter 6

Price of Hydrogen.

The future price of hydrogen was derived from Aurora Energy Research (Aurora Energy Research, 2023). The forecast presented in graphical form was digitised using the plotdigitizer app (Plotdigitizer.). The parameters for the time series derived from this data were:

Parameter	Value
Initial Price	£3.15 per Kh H
Underlying rate of change	-£.043 per Kg H per year
Standard Deviation	0.03

Price of Electricity.

Forecast for the future price of electricity was sourced from BEIS (Department for Business, 2022). The parameters for the time series derived from this data were:

Parameter	Value		
	High Scenario	Base Scenario	Low Scenario
Initial Price	£73 per MWhr	£56 per MWhr	£45 per MWhr
Underlying rate of change	-£0.25 per MWhr per year	£0.17 per MWhr per year	£0.26 per MWhr per year
Standard Deviation	.0.025	.0.025	.0.025

Price of Electrolysis Plant

Data for the capital cost of the electrolysis plant was obtained from the World Energy Council (World Energy Council 2021.) . Again, the plotdigitizer app was used to convert graphical time series to a numeric form for high and low price scenarios. A mean time series was derived by calculating the mean values of these two series.

The derived time series are:

	High (£ per Kw capacity)	Mean (£ per Kw capacity	Low (£ per Kw capacity
2020	1440	1180	920
2021	1408	1140	872
2022	1376	1100	824
2023	1344	1060	776
2024	1312	1020	728
2025	1280	980	680
2026	1248	940	632
2027	1216	900	584
2028	1184	860	536
2029	1152	820	488
2030	1120	780	440
2031	1096	761	426
2032	1072	742	412
2033	1048	723	398
2034	1024	704	384
2035	1000	685	370
2036	976	666	356
2037	952	647	342
2038	928	628	328
2039	904	609	314
2040	880	590	300
2041	856	571	286
2042	832	552	272
2043	808	533	258
2044	784	514	244
2045	760	495	230
2046	736	476	216
2047	712	457	202
2048	688	438	188
2049	664	419	174
2050	640	400	160

2051	616	381	146
2052	592	362	132
2053	568	343	118
2054	544	324	104
2055	520	305	90
2056	496	286	76
2057	472	267	62
2058	448	248	48
2059	424	229	34
2060	400	210	20

Price of Sequestration Plant

Data for the prices of carbon sequestration plants were obtained from the work of Shackley and colleagues (Shackley et al., 2011b). This data, in terms of cost per tonne of feedstock, was scaled to match a plant of the size considered. This results in a price of £200 per tonne of feedstock per year.

References for Annex G

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