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# A novel investment and valuations-led approach to forecasting hydrogen energy market development and the application of the model to Scotland's Energy Balance

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## Copyright Statement

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# Contents

# Table of Figures

# List of Tables

# Abstract

It is generally recognised that the primary tools being utilised for hydrogen energy forecasting and policy development today are those principally developed for centralised planning (historically for the nationalised energy industry) taking a least-cost approach. While useful tools for comparing the viability of different technologies from a cost perspective, these approaches do not attempt to consider the potential value contribution that such technologies could offer companies and, by inference, the likelihood of their receiving investment.

The author proposes a novel model for forecasting the deployment of hydrogen energy systems based on a company value maximisation algorithm, designed to assist governments and other industry players in decision-making and the development of appropriate policy instruments. Current cost-minimisation approaches, such as MARKAL, have limitations particularly where price arbitrage between energy streams exists. A theoretical relationship between market sector valuations and investment activity is developed and the model is subsequently applied to the Scottish hydrogen energy market. Through the utilisation of 3 value impact metrics, namely net present value, earnings per share, and revenue and profitability multiples, the impact of investing in hydrogen energy infrastructure projects on 13 key market competitors is considered. The key findings can be summarised as:

1. The model suggests that hydrogen plant could be NPV positive, and hence developed, sooner than the cost analyses presented, for example, in the UK Strategic Framework for Hydrogen would suggest.
2. In contrast to the findings in (1), the model points to higher value metrics for electricity plant in the base case suggesting companies presented with a choice would tend to invest in electricity over hydrogen. However, there are pricing conditions where the hydrogen plant are competitive with electricity plant in terms of NPV, EPS contribution or sum-of-the-parts contribution.

3. The sensitivity analysis points to discrepancies in the levels of support being provided to electricity infrastructure and transport fuel infrastructure. Examination of the relative effects of different policy measures in the electricity and transport fuel markets on the value of different investments demonstrate the utility of the model in identifying and assessing counter incentives within these potentially converging markets.

4. The propensity to invest in hydrogen plant differs according to the characteristics of the company looking to make the investment which again has implications for policy-makers. There is, therefore, merit in looking at development from the perspective of specific companies and different value measures as results are not consistent.

5. The potential that hydrogen energy offers a utility company to add value to an investment in electricity generation infrastructure has been demonstrated through a specific example. This contrasts with the systems based approach which would tend to consider each technology individually and in comparison with directly competing technologies.

# 1 Introduction

## *1.1 Research Context and Motivation*

The work in this Thesis was driven by an initial premise that current approaches to forecasting the deployment of hydrogen energy systems were incomplete and failed to take account of the investment behaviour of companies in a competitive market. As will be discussed in the following sections, the author felt that there was merit in exploring and developing an alternative approach to modelling market development which took into account these aspects and which, therefore, might be more representative of future growth.

It will be argued in this Thesis that the primary tools being utilised in energy forecasting and policy development today are those principally developed for centralised planning (historically for nationalised energy industries) taking a least-cost approach. However, as Botterud eloquently states in reference to electricity markets [1]:

"…the centralized least-cost planning approach does not reflect how investment decisions are made…where several…companies are competing with each other…"

Botterud goes on to point out that some observers:

"...would argue that a well-functioning…market would converge toward the optimal expansion plan…[while others would]…contend that the independent and decentralized decision-making…leads to suboptimal…plans".

Implicit in this statement is the assumption that in the centralised least-cost planning model, minimum cost is the optimal state and, under many conditions, this may be legitimately considered as a primary policy objective. However, in a competitive energy market made up of autonomous actors, for example producers, investors and consumers, the definition of optimal will be a function of a given actor's specific objectives. In the case of commercial energy producers, it might be assumed that the optimal solution would be that which maximises shareholder value and while this solution is potentially consistent with system cost-minimisation (the cost optimal solution) it is unlikely to be the only possible solution. Even from the perspective of policy-makers, the question of what is optimal is not clear cut as reference to policy measures to stimulate the introduction of renewable electricity generation, for example, confirm. In this case the minimum cost objective is, and many would argue should be, subordinated to other more critical concerns. Thus, governments might have an interest in maintaining "artificially" high energy prices or encouraging the introduction of apparently uncompetitive energy sources in order to achieve other, more pressing, policy goals. However, it is argued that if the underlying model fails to imitate the behaviour of the market actors the results obtained will be unrepresentative of market development regardless of the objective.

Despite the general drive towards increasingly liberal, capitalistic energy markets, government forecasting still relies heavily on planning tools which seem better suited to centrally controlled, centrally planned energy systems. Recognising the limitations of such an approach, there is interest being shown in alternative approaches to forecasting market development that have at their heart the behaviour of the firm [1] [2]. This interest is further fuelled by the increasing complexity evident in energy markets resulting from changes in market practices, the fiscal regime or the introduction of new technologies. While it is recognised that the evolution of system costs will undoubtedly influence the introduction of new technologies, it is argued that an equally important factor will be the opportunity the technology represents for market participants to maximise (or at least to generate satisfactory) returns. Thus the systems-based analyses which see the introduction of new technologies as a function of their cost-competitiveness with respect to alternatives may be misleading. Many factors influence the share price (and hence equity returns or shareholder value) of a company including earnings per share, revenue growth potential and, importantly, the sum of the Net Present Value of all the projects being developed (or to be developed) by the company. Hence there is a need for a broader analysis which encompasses these factors.

With this context in mind, the author has addressed these issues through the development of an approach that is company-centric and has value maximisation as its primary objective. As will be seen, this model has the ability to provide an alternative view of market development and potentially aid policy makers to better formulate market interventions.

## *1.2 Economic Backdrop*

As was briefly mentioned in Section 1.1, the interest in alternative modelling techniques for the energy industry is, in part, driven by the multiple underlying challenges facing the energy industry in the UK [3]. There is a recognised need firstly to better forecast future market development and secondly to design policies to more successfully enable the achievement of government targets. In the words of the UK Strategic Energy Review in 2006 [4]:

"A clean, secure and sufficient supply of energy is simply essential for the future of our country."

In accordance with this overall objective, among the UK Government's current specific policy objectives are greenhouse gas abatement, network stability and fuel security, while market regulation is designed, in the words of the electricity and gas regulator, "to promote choice and value" [5], in other words to create a competitive market offering consumers the optimal combination of price and quality. Since 2000, a number of exogenous challenges have come to the fore, affecting the objectives set out above including declining reserves of oil and gas on the UK Continental Shelf (UKCS), fuel price volatility and, crucially, a lack of financial liquidity.

This last point is particularly significant to the author's Thesis since it serves to highlight the importance of examining the flow of investment capital into companies when forecasting market development. The reduction in the supply of credit (the so-called Credit Crunch) has had the effect of reducing the level of liquidity in the market and increasing the cost of debt [6]. By extension, the supply of equity capital may also be reduced not least since the business model of private equity providers is predicated on the ample supply of inexpensive debt necessary to boost equity returns. The knock-on effect from the Credit Crunch and the subsequent economic downturn has also had a deleterious effect on company valuations, especially in the emerging energy markets [7], and this has meant that the cost of equity capital has also increased creating extremely unfavourable conditions for investment.

This unique combination of circumstances throws into sharp relief the shortcomings apparent with traditional methods of forecasting energy market development. Nowhere is this more evident than in the case of low-carbon technologies which will enable the UK to address the dual concerns of greenhouse gas emissions reduction and energy security. The relatively early stage of development of these technologies and their potentially disruptive nature, combined with the fact that (with certain exceptions) they do not currently represent a compelling investment story, makes understanding how to effectively stimulate their early deployment in the current economic climate of crucial importance. In consequence, the author considers the development of the value-maximising model as particularly timely.

## *1.3 Basis in Literature*

A comprehensive review of hydrogen economy modelling, energy systems modelling and financial investment theory was undertaken to establish the novelty of the author's work, and this is described in detail in Section 2.6. However, in order to put the contributions of the Thesis into context, certain aspects of the literature review are introduced in Section 1.3.1.

### 1.3.1 Concepts and Modelling of the Hydrogen Energy Economy

In essence a move to a hydrogen energy economy could be understood as a shift towards hydrogen becoming a major fuel vector (or carrier, similar to electricity) and satisfying a significant proportion of end-user demand for energy. However, for all practical purposes this description is rather too simplistic and not particularly relevant to any analysis of the impact on the UK economy of a major shift, domestically or globally, towards the application of hydrogen in the energy value chain. This Thesis seeks to explore the economic characteristics of each element of the hydrogen energy value chain and how businesses in each part of that chain can contribute to GDP and to value creation. Figure 1.1 below shows the possible elements making up the hydrogen energy value-chain.

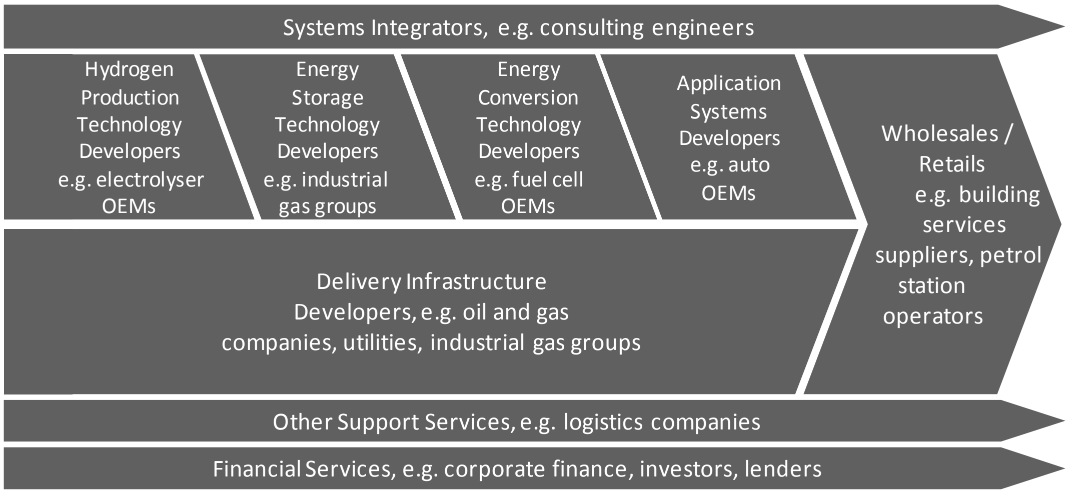



**Figure 1.1 Hydrogen Energy Value Chain**

Opportunities exist within the UK to develop businesses in any or all of the market areas represented in the Figure 1.1 and accordingly a hydrogen energy economy could refer to one where one or more of these technologies or services are developed or deployed in the UK. It would be possible, for example to develop competences in any given area without there being a wholesale shift towards the implementation of a hydrogen infrastructure in the UK. Extensive literature on the so-called "hydrogen economy" exists and McDowall and Eames [8] provide a very useful review of extant literature and further propose a framework for critical analysis of work carried out to date. This typology is considered a satisfactory one for the current literature review and is summarised as follows:

<u>Descriptive Models</u>

As the name suggests, such models aim to describe future scenarios based on extrapolation of current trends or analysis of key industry drivers. McDowell and Eames point to three different types of descriptive model namely Forecasts, Exploratory Scenarios, and Technical Scenarios.

Normative Models

Unlike descriptive models, normative models set out a vision for the future and investigate the steps that would need to occur in order for such a vision to be achieved. Once again, three categories are proposed namely Visions, Backcasts & Pathways and Roadmaps.

In addition to the hydrogen economy literature referred to here, there is considerable body of quantitative research that forms part of the wider cost-based energy modelling favoured in traditional energy sectors and this is described in more detail in Section 1.3.2.

### 1.3.2 Background to Energy Economic Modelling

Techniques for forecasting the development of different energy systems in the UK are firmly grounded in the approach of central planners [9]. There is recognition from a number of quarters that current least-cost algorithms for modelling market development such as MARKAL [10], MAED [11] and WASP [11] are incomplete and may fail to satisfactorily interpret the behaviour of energy firms in privatised markets [1]. Consequently, the ability of these algorithms to provide a satisfactory representation of energy development is limited and several research groups have been exploring alternative approaches centred round alternative objective (or utility) functions. However, notwithstanding the fact that the supply of fuels for transport and heating has for decades been driven by private enterprise and that privatisation of the electricity supply industry (ESI) occurred some 20 year ago, little attempt has been made to modify the way in which the energy sector is modelled at Government level. In particular, little attempt has been made to build models that replicate the behaviour of capitalistic firms acting to maximise shareholder value in a competitive (albeit sometimes regulated) market. Traditionally, the key objective of the central planner has been to ensure that the lowest cost combination of energy technologies is provided, subject to security constraints, and the tools at the planner's disposal reflect this. Since the central planner is primarily concerned with the use of technology and with energy as an input to other parts of the economic system (e.g., industry or householders) the models they use solve for minimum system cost on the basis that this maximises GDP. There is an implicit assumption within this approach that in the world of private enterprise, the least-cost mix of energy technologies would be favoured by investors, a view which has certain limitations that will be discussed in Section 2.6.5.

The core tool used by UK central government in energy forecasting is the Market Allocation ("MARKAL") model which forms the backbone of much of the quantitative research into traditional and future energy systems [9]. A significant proportion of the modelling work on hydrogen energy futures (led by the Department for Business Enterprise and Regulatory Reform and the Policy Studies Institute) has centred on the integration of hydrogen into the broader analysis of UK energy sources and uses, built around the MARKAL modelling tool [12]. A number of other important bodies of work on hydrogen energy have been carried out using the MARKAL model such as Tseng et al [13] and the recent Hyways research for FP6 [14].

As has been described, the MARKAL model is concerned primarily with energy as an input to economic activity rather than considering the energy-related industries as generators of GDP in their own right. There is an implicit assumption in these analyses that if the hydrogen energy system becomes cost competitive, and therefore introduced into the mix of energy sources and carriers, that development will inevitably occur. What this further pre-supposes is that there will be a flow of capital to hydrogen systems allowing development to take place. These assumptions would appear to be unsubstantiated and the author's investment-led approach seeks to test this premise. In addition, the cost-based analyses explicitly ignore the relative contribution that energy systems could make to the economy as a whole, which might ultimately be superior for hydrogen energy systems as compared with others. This aspect is also explored in the author's Thesis.

### 1.3.3 Investment and Finance Theory

Two key strands of investment and finance literature are relevant to the current research, namely research related to physical investment and research pertaining to shareholder returns. These bodies of work provide theory and evidence with respect to the investment behaviour of firms and the factors affecting the appreciation or depreciation of their shares or the behaviour of securities markets. In the following sections three key areas of research are described that are pertinent to the current analysis and which help support the author's principal value-maximising approach.

#### 1.3.3.1 Underpinnings of value-maximisation

The neo-classical view of investment behaviour, first put forward by Jorgenson [15], states that companies are driven to maximise the present value of future after tax receipts (roughly equivalent to future cash flows) as shown in Equation (1.1).

$$V(0) = \int_{t=0}^{\infty} e^{-rt} \left[P(t) - D(t)\right] dt \quad \textbf{(1.1)}$$

where
*V(0)* = Value of the business at time t = 0
*P(t)* = Pre-tax cash receipts in period t in currency units
*D(t)* = Taxes in period t in currency units
*r* = Discount rate as a fraction
*t* = time, in years

Intuitively, this can be understood to be broadly equivalent to maximising the Net Present Value of all current and future projects a company has at its disposal (see Equations (1.2) and (1.3) since the after tax receipts of the company are roughly equal to the sum of all cashflows from all projects.

$$V(0) = \int_{n=1}^{N} NPV(n) \quad \textbf{(1.2)}$$

where, NPV(n) is the NPV of the $n^{th}$ project of N defined by Equation (1.3).

$$NPV(n) = \sum_{t=0}^{x} \left[ \frac{CF_n(t)}{(1+r_n)^t} \right] + \frac{RV_n}{(1+r_n)^{x_n}} - I_n \qquad \textbf{(1.3)}$$

where

$CF_n(t)$ = Cash flow in period t to $n^{th}$ project (of N) in currency units

$r_n$ = Discount rate (or Expected Return) for $n^{th}$ project as a fraction

$RV_n$ = Residual value at the end of the $n^{th}$ project in currency units

$I_n$ = Initial investment for $n^{th}$ project in currency units

$x_n$ = Lifetime of the nth project in years

#### 1.3.3.2 Propensity to invest

While the equations in Section 1.3.3.1 demonstrate how a company might approach an investment decision as a means to maximise value they say little about a company's desire to invest. It has been proposed by Tobin [16] that the propensity for a company to invest at a given point is determined in time by the extent to which its market capitalisation exceeds the value of its invested capital (see Equation (1.4).

$$Q = \frac{(ME + BVL)}{(BVE + BVL)} \qquad \textbf{(1.4)}$$

where

$Q$ = Tobin's Q expressed as a fraction

$ME$ = equity market capitalisation in currency units

$BVL$ = book value of liabilities in currency units

$BVE$ = book value of equity in currency units

The company's Q value could be considered to measure how highly the company is valued by the market and it can be understood intuitively that if the market values a company more highly than its underlying physical assets there should be a willingness to grow those assets until the balance is restored. More recently, it has been proposed (see Hyashi [17]) that Tobin's Q-theory and the neo-classical approaches are, in fact, equivalent in the presence of adjustment costs. This aspect is discussed in Section 3.4.3 with respect to the price-earnings (PE) ratio value measure.

#### 1.3.3.3 Factors affecting shareholder return and risk

The returns to a company's equity are clearly influenced by a number of factors and a wide range of analyses has been performed by theoreticians and practitioners alike to explain what drives valuations and hence returns to the equity of a company. Perhaps the most fundamental literature surrounds the Capital Asset Pricing Model (CAPM) put forward in the 1960s [18] which describes the relationship between equity return and risk, as measured by correlation with the market. The CAPM relationship is described algebraically in Equation (1.5).

$$E(r_i) = r_f + \beta\big(E(r_m) - r_f\big) \qquad \textbf{(1.5)}$$

where

$E(r_i)$ = Expected return on equity as a percentage

$r_f$ = Risk free rate of return as a percentage

$E(r_m)$ = Expected return on the market as a percentage

β = Correlation between the volatility of the equity and the market as a fraction

The correlation of the returns to the given equity and the market as a whole can be measured empirically and is defined by the relationship in Equation (1.6).

$$\beta = \frac{cov(r_i, r_m)}{var(r_i)} \qquad \textbf{(1.6)}$$

The theory initially appeared to be supported by empirical evidence but more recently (since the early 1990s) the data and theoretical predictions have diverged and other observers have pointed to the influence of other parameters such as absolute size, degree of leverage and historical price-earnings ratio. French and Fama in their seminal work [19] provide a review of a number of these influences and offer more complete empirical evidence as to the effect of each. Most interesting for the current analysis is the potential role of the PE in determining return since it is argued in this Thesis that the relative valuation (according to the PE and possibly other metrics) of a company has a direct influence over the inflow of investment capital to that company and its propensity to invest in physical assets. The French-Fama model can be described by the function in Equation (1.7).

$$r_i = fn\{NPV_i, \beta_i, PE_i, ME_i, L_i\} \tag{1.7}$$

where

$r_i$ = return on the equity of company i, as a fraction

$NPV_i$ = NPV of all company i's activities, in currency units

$\beta_i$ = the stock volatility relative to the market for company i, as a fraction

$PE_i$ = price earnings ratio for equity of company i, as a fraction

$ME_i$ = equity market capitalisation of company i, in currency units

$L_i$ = ratio of debt to ME (leverage) of company i, as a fraction

## *1.4 The Company-Centric Investment-Led Approach*

In response to the issues raised in the preceding sections, the author has developed a novel simulation model that has at its core the concept of company value maximisation. The model considers the investment patterns of energy companies but also, by extension, their fund-raising activities and the inflow of commercial capital. It aims to capture the effect of not only the cost differentials but also the pricing differentials that exist between different areas of the energy sector and associated with different technologies. It further seeks to explore the effects of different policy initiatives with specific reference to the impact on financial and physical investment.

### 1.4.1 Features of the Investment-Led Approach

In the same way that the cost-optimisation model seeks to balance supply and demand with a portfolio of least cost supply infrastructure, so the value-optimisation model, recognising that companies will seek to maximise shareholder value, solves for a portfolio of supply infrastructure that meets demand and serves to maximise the shareholder value of companies in the sector. This company-centric investment-led approach is based around the concept that a market develops as a function of the companies operating within that market and that companies are driven by the desire to maximise shareholder value above all other considerations. In contrast to the systems-based cost-led approach, investment in infrastructure will reflect its ability to add value to the companies investing in capacity and not the cost of one system relative to another. Based on the prevailing theory described in Section 1.3 and culminating in Equation (1.7), the value of a company's equity after a time t = 1 has elapsed ($ME_{t=1}$), with respect to its value at t = 0 in the absence of dividends would be given by Equation (1.8):

$$ME_{t=1} = ME_{t=0} \times r(I_t) = SP_{t=0} \times r(I_t) \times NS_{t=1}(I_t) \qquad \textbf{(1.8)}$$

where

$ME_{t=1}$ = Equity market value at time t = 1 in currency units

$ME_{t=1}$ = Equity market value at time t = 0 in currency units

$SP_{t=0}$ = share price at time t = 0, in currency units

$NS_{t=1}(I_t)$ = number of shares in issue at time t = 1

$r(I_t)$ = the return in time period t as defined by Equation (1.7), as a percentage

$I_t$ = investment made in period t, in currency units

The maximisation function would then be described by Equation (1.9) although it should be noted that this would locate all the inflection points both maxima and minima and therefore this is a necessary but insufficient condition. In any case, the model does not attempt to solve for this differential equation but rather explores trends and directional outputs.

$$\frac{\partial ME}{\partial I} = 0 \qquad \textbf{(1.9)}$$

The logic of the analysis is that for each increment in investment by a company there will be a resultant increase in the equity market value (if the investment is value-added) based on the returns function described in Equation (1.7). This relationship can be expressed as shown in Equation (1.10).

$$\frac{\Delta ME}{\Delta I} = \Delta r \times \Delta NS \qquad \textbf{(1.10)}$$

One important facet of this is that not all investments can be treated equally with the implication being that the increase in market value resulting from one unit of investment in one system will in all probability be different from the resulting increase from investment in another. What is more, the resulting increase in value attributable to investment in a given system will be different depending on which company is making the investment.

### 1.4.2 Application of the Model

Having discussed the theoretical basis for the analysis, these building blocks are utilised in this Thesis to:

1. Build and test the performance of a model for hydrogen and fuel cell sector development based around this value-led model; and
2. Apply that model to the case of Scotland under a number of scenarios.

It has been argued above that the increasingly complex energy industry demands alternative approaches to analysing and forecasting market development. In particular, more effective tools are required to understand and model the relationship between government policy initiatives and the resultant <u>physical investment</u> in, and <u>capital flow</u> towards, each area of energy infrastructure. This might be particularly apparent when forecasting hydrogen and fuel cell developments in light of the disruptive nature of these technologies and the imputed blurring of traditional boundaries between energy systems. Hydrogen presents, for example, the opportunity for electricity utilities which have had margins and growth constrained by regulation and market dynamics to enter other fields like transport fuel where the market dynamics are different and, potentially, less constrained. This offers the potential for additional growth and potentially improved margins but also represents a challenge to established levels of return and risk profiles associated with utilities which can be explored through the model. The model has as its starting point a forecast for potential energy demand, including for hydrogen. The model then considers the value contribution over successive periods of various investment options available to each of the potential investee companies according to the methodology proposed and builds a supply capacity curve accordingly until demand is met. Instead of considering only the cost data associated with various infrastructure types, the model is built from "Project Capsules" that contain information about NPV, revenues and profitability associated with these different options which are combined to build up value contributions ($\Delta$ME) as defined in Section 1.4.1. The strategies that offer greatest value contribution to each company would be assumed to be chosen and the overall resulting level of hydrogen production infrastructure is arrived at by summing all the individual contributions from each company. The resultant value contributions from different business mixes are compared and tested under various price and cost conditions as well as a number of scenarios.

The application of the model includes a number of significant simplifications at this stage which include:

1. Focuses on the behaviour of a limited number of businesses in 3 defined sectors presented with options regarding the supply of electricity or hydrogen which could be produced from either natural gas or electricity. The principles of the model are not affected by the restriction on the number of sectors considered and analysis of the performance of companies in the 3 chosen sectors (see Section

7.3) demonstrated sufficient variability to allow a thorough testing of the approach;

2. No account is taken of the competitive response of industry players and it is assumed that the market in question is occupied by the 13 key players currently identified, each of which attempts to maximise the value contribution from investment activities. Given that investment decisions for given projects will typically be made on their own merit without reference to what competitors might be planning (in any case this information may only be available to competitors once a project has begun) this constraint should not affect the overall thesis;

3. In the case of natural gas and electricity, the potential future applications are limited to the current ones or the production of hydrogen. The model is not designed to compare the relative attractiveness of different end-user applications but instead to consider the investment proposition represented by hydrogen production if a certain level of demand and, as such, the constraint would not affect the functioning of the model;

4. The application of hydrogen is directed primarily to the unregulated transport fuel market but with the opportunity to supply heat as well. Since the model considers the investment proposition on a project by project basis then this restriction has no effect on the outcome; and

5. The model limits itself to the production of hydrogen only and does not consider other parts of the hydrogen value chain like fuel cell manufacturer or integration which might also contribute value to the economy as a whole. It was considered reasonable to consider different parts of the value chain in isolation from one another on the basis that the development of one part of the value chain should not directly influence development in another at the project level.

These simplifications and constraints were adopted for a number of reasons but primary among them was the desire to create a model that would be sufficiently complex to allow the author to test the approach but at the same time simple enough to be developed within the timeframe available. Since the approach is built around an understanding of the relative value offered by different investment options and the decision to limit the number of options available or the number of companies to which the opportunity is open should not have an impact on the understanding of how the model functions. While these boundary conditions are in some cases relatively severe none was considered to adversely affect the testing of the Thesis for reasons explained. It is anticipated that some, if not all, of these constraints can be relaxed in future iterations of the model as will be discussed in Section 6.2.

## *1.5 Aims and Objectives*

The hypothesis put forward by the author is that in energy markets where the allocation of capital is the preserve of individual private companies seeking to deliver maximum returns to their shareholders, that a model built around the investment behaviour of those companies should offer a more representative picture of future market development than current systems based, cost driven approaches. The author has set out to describe a methodology designed to reproduce the investment decisions of companies with the aim of understanding:

a) whether it was feasible to develop a model of this type;

b) in what way the results of such a model might differ from those obtained from a cost optimisation approach; and

c) whether the methodology is in some way "better" than current alternatives?

In order to test this hypothesis which would appear to have intuitive merit, the author has implemented a software model built around the conceptual framework and applied it to a particular market. The market chosen is hydrogen fuel and its application primarily to the transport sector in Scotland. Hydrogen is one of a number of proposed low carbon alternatives to fossil fuels especially for transport and Scotland, which has a rich renewable electricity generation resource and has the capacity to produce significant excess electricity, is well placed to develop the production of clean hydrogen. Hydrogen energy has the capacity to address the dual challenges of energy security and emissions reductions but also could be seen as a replacement industry for the oil and gas sector which is in decline in the UK. The results have then been compared with what would be anticipated from other types of modelling. In addressing the overall research questions identified above, this Thesis sets out to address the following specific key issues.

1. Critically examine existing approaches to forecasting the development of alternative energy technologies;
2. Develop a novel theoretical model for studying and forecasting the relationship between alternative energy market dynamics, investment returns and funding potential;
3. Utilise the validated model to forecast development of the hydrogen and fuel cell sector in Scotland; and
4. Explore how the forecasts differ from traditional projections and consider the effects of policy measures under the investment-led and cost-led analyses

## 1.6 Contribution to the Field

The author claims the following novel and identifiable contributions to the field of energy sector economic modelling and forecasting.

1. Using established theoretical frameworks for describing physical and financial investment, the author has developed a novel approach to modelling the potential future levels of investment in the hydrogen and fuel cells industries in the UK. In contrast to existing models, many of which have cost-minimisation algorithms as their basis, the author's new approach is built around the shareholder value-maximising behaviour of firms and proposes an algorithm that relies on the premise that new technologies will be introduced according to the extent to which they represent opportunities for shareholder value creation. Recognising the importance of the performance and investment behaviour of companies in the energy sector to the development of hydrogen and fuel cells in the model, the author has undertaken a systematic analysis of the performance, financial and returns characteristics of companies across the energy industry including the

hydrogen and fuel cells sectors in the UK and the US over a 3 year period. This has highlighted significant differentials across the sub-sectors observed which might be exploited by companies in the sector and has led to certain conclusions about the likelihood of development in hydrogen and fuel cells progressing successfully.

2. The author's model has been applied to the case of the Scottish energy market recognising the particularly attractive aspects of Scotland's energy balance to the production of renewable hydrogen. For the first time, a model of this type has been used to explore possible future deployment of hydrogen and fuel cells infrastructure in Scotland, based on existing expectations for the development of consumer demand. The results of the analysis justify the application of the author's new approach since they highlight the effect of a wide range of input variables, several of which are not related to the levelised cost, on the absolute and relative investment value represented by hydrogen production technologies. Based on the results of the analysis, the author goes on to discuss the effects of possible measures and whether they are likely to meet government expectations in terms of achieving goals with respect to low-carbon technologies and to highlight some potential for perverse incentives inherent in the market.

## *1.7 Thesis Outline*

Chapter 2 of this Thesis provides an insight into the issues facing the energy industry in the UK and the role that hydrogen could play in the future development of the energy sector as Government and industry players work to address the issues of carbon emission reduction and energy security. In addition it offers an extensive review of the literature relevant to the current research and describes the novelty of the author's model in the context of this literature. Chapter 3 describes the model developed by the author, positions it relative to other models being used to forecast energy industry development and offers a detailed description of the model implementation. Chapter 0 presents the basic results of the model and analyses the implications while Chapter 5 completes the forecast and other comparative analyses.

Finally in Chapter 6 the author provides some overall conclusions and suggests some further areas for research.

## 1.8 Associated Publications and Grants

The author received funding from the Engineering and Physical Sciences Research Council (EPSRC) under a Doctoral Training Award for this research and secured additional funding from Scottish Power which has been an active partner on the project. The author has successfully published work in academic journals and at related conferences and a list of associated publications is provided below.

Furthermore, the author was recently part of a responsive mode bid to EPSRC entitled *"Development of a Multi-Agent Investment-Driven (MAID) Modelling Tool to aid the definition of value-maximising renewable hydrogen energy strategies and associated market adjustment policies"* to develop a multi-agent adaptation of the investment led model, underpinned by the work in this Thesis.

### 1.8.1 Journal Publications (Published)

1. *Houghton T and Cruden A* (2010) Development of a novel market forecasting tool and its application to hydrogen energy production in Scotland. International Journal of Hydrogen Energy. In press. (doi:10.1016/j.ijhydene.2010.04.103)

2. *Houghton T and Cruden A* (2009) An Investment-Led Approach to Modelling the Development of Hydrogen Energy in the UK. International Journal of Hydrogen Energy Vol. 34, Issue 10 Pages 4454–4462 (doi:10.1016/j.ijhydene.2008.12.041)

3. *Cruden A et al.* (2008) Fuel cells as distributed generation. Proceedings of the Institution of Mechanical Engineers Part A-Journal of Power and Energy Vol. 222 Issue A7 Pages 707-720 (doi:10.1243/09576509JPE609)

### 1.8.2 Journal Publications (Accepted)

1. *Houghton T and Cruden A* (2010) Exploring Future Hydrogen Development and the Impact of Policy: A Novel Investment-Led Approach. Energy Policy.

### 1.8.3 Conference Papers

1. *Houghton T and Cruden A* (2009) The development and application of a shareholder value impact model: could the production of hydrogen transport fuel offer value creation opportunities to an electricity utility? Proceedings of the World Hydrogen Technologies Convention, Delhi, India

2. *Houghton T and Cruden A* (2007) An Investment-Led Approach to Modelling the Development of Hydrogen Energy in the UK. Proceedings of the World Hydrogen Technologies Convention, Montecatini, Italy

3. *Houghton T and Cruden A* (2008) Value Driven Investment into Hydrogen and Fuel Cells. Proceedings of the National Hydrogen Association Fall Forum

4. *Houghton T and Cruden* A (2007) An Investment-Led Approach to Hydrogen Energy Development. Proceedings of the Grove Fuel Cell Symposium, London, UK

5. *Houghton T and Cruden A* (2007) Investing in Hydrogen – Pointers from the IT industry. Proceedings of the H207 at All Energy Conference, Aberdeen, UK

# 2 Energy Industry Economics and Literature Review

In order to define the boundaries of the current research and to understand the economic impact that the energy industry has on the UK economy as a whole, this Chapter of the Thesis provides an overview of the energy industry and defines some of its key issues. Since the approach taken in the analysis is holistic and aims to provide a forecast of growth in the hydrogen energy industry based around value creation, it is critical to understand the current contribution that the energy industry makes to the wealth of the UK, in general, and Scotland, in particular. A number of different approaches could be taken for considering the economic contribution made by a given industry but for the purposes of this analysis, the UK energy industry is considered from the point of view of its component companies. The set of companies could be defined either narrowly or broadly depending on the objective of the analysis and in this initial overview a relatively wide definition is proposed that encompasses not only the core energy companies but also those that provide supporting products and services. Figure 2.1 provides an overview of the different industrial activities making up the energy industry that are considered and discussed in this market overview. This chart serves to highlight the multiplicity of activities involved in the production and delivery of energy, all of which represent opportunities for firms to create value and all of which contribute to GDP. Energy businesses may be divided into five rough groupings, namely primary energy producers and processors, energy deliverers including electricity generators, energy technology manufacturers, supporting services providers and the providers of financial services and capital. These different companies make up "the energy industry" with the finished products being supplied to end customers, which may either be domestic or business consumers. Since there is also a significant element of duty (or taxation) which must be paid by the market participants, HM Revenue and Customs is also represented in the chart for the sake of completeness. Certain of the inter-relationships between industry players are represented in Figure 2.1, specifically the flow of goods and services, the flow of capital and the flow of taxes and duties; what is omitted is the flow of payments for goods and services which is implied in the supply of goods and services.

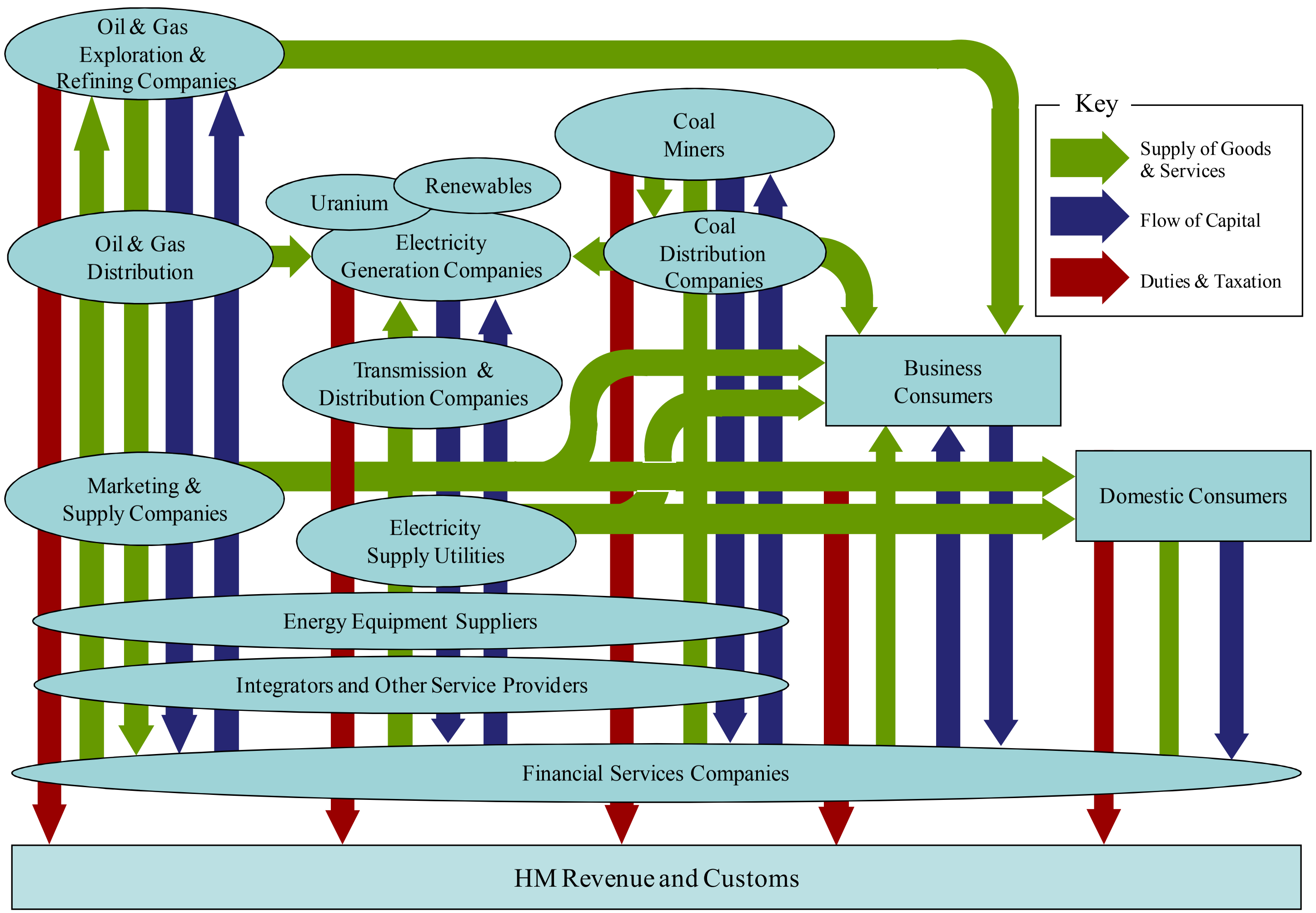



**Figure 2.1 The UK Energy Industry: Inter-relationships, Physical and Financial Flows**

## 2.1 The Size and Shape of the Energy Industry in the UK

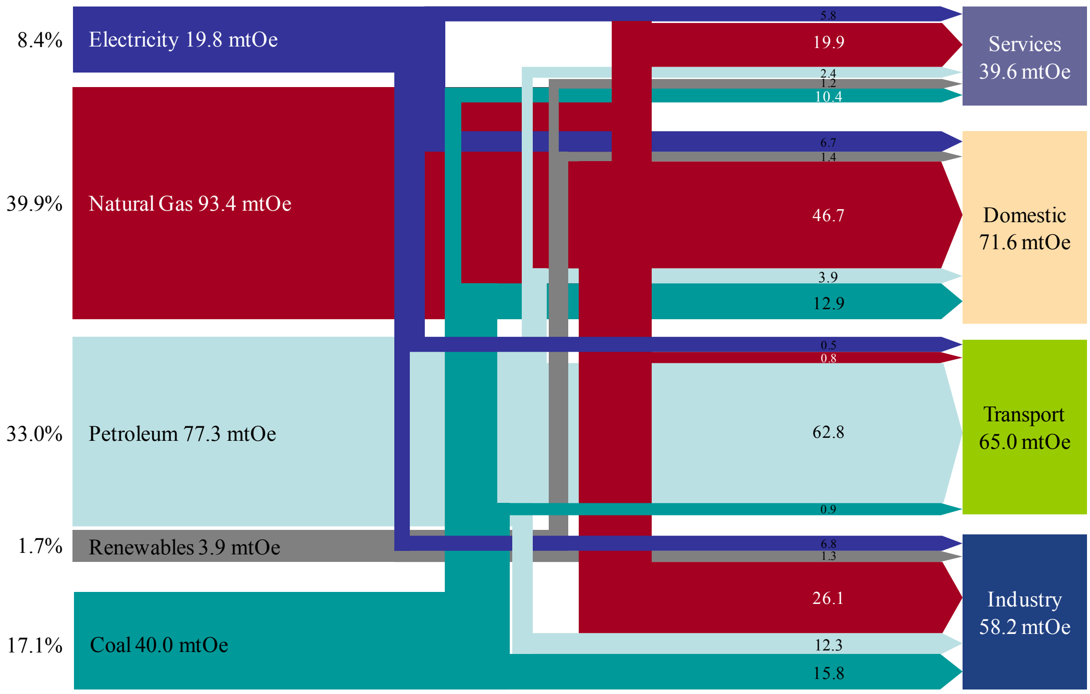
In order to quantify the impact of the energy industry on UK economic activity, this research considers three aspects, namely:

1. the scale and patterns of the nation's energy usage;
2. the GDP contribution of energy related activities; and
3. the role of energy within the context of savings and wealth.

The UK has companies directly involved in a broad spectrum of energy activities that contribute to GDP and is at the same time a significant consumer of energy. In 2008 amongst OECD countries the UK was the 6$^{th}$ largest consumer of energy and the 5$^{th}$ largest producer [20] of crude oil. The UK continues to exploit significant (albeit declining) oil and gas reserves in its coastal waters and two of the world's largest oil and gas companies, Shell and BP, have their headquarters in the UK. The UK also has one of the largest petroleum exchanges in the world and the London Stock Exchange (LSE) hosts several other international oil and gas companies. It is home to numerous world-leading oil and gas services companies and provides a host of financial services to energy sector companies. It was one of the pioneers in liberalising its electricity generation and supply sectors [21] and boasts a number of highly successful energy technology manufacturers. At the same time, the contribution of the oil and gas and utilities sectors to the capital base in the UK is very significant and BP alone accounted for 25% of all the dividends paid by FTSE 100 companies in 2009 [22]. Consequently the energy sector can be considered to represent a sizeable repository for the nation's wealth. Each of these factors is discussed in the following sections of this Thesis in order to provide a more complete picture of the investment environment. The context provides both evidence of the need for government intervention to support alternative energy developments and a concomitant opportunity for companies and providers of capital seeking to invest in the sector.

### 2.1.1 Scale and Patterns of Energy Usage

In terms of energy usage, the UK is heavily reliant on fossil fuels, with more than 90% of all primary energy being supplied from fossil sources. The Sankey Diagram in Figure 2.2 indicates the total energy supply by fuel type and by end-use which confirms the almost complete reliance on fossil fuels. Indeed with only a relatively modest proportion of electricity generation being attributable to renewables (including hydro) the only significant non-fossil element of the overall energy mix is nuclear power which accounts for roughly 8.4% of primary energy demand. In terms of consumption, demand is split roughly into thirds between businesses, consumers and transportation. The commercial and domestic sectors are currently highly reliant on natural gas with approximately 50% of all demand in these sectors being met from this source. Similarly, the transport sector is highly reliant on oil (95%) reflecting factors such as the high dependence on road transportation and the limited penetration of electricity into the public transportation sector.




*Source: DECC Energy Statistics 2007[31]*

*All amounts in millions of tonnes of oil equivalent (mtOe)*

**Figure 2.2 UK Energy Sources and Uses Sankey Diagram**

In this context it is useful to compare Britain's energy usage patterns with other developed nations in order to assess their relative reliance on fossil fuels and the extent of their energy independence. Figure 2.3 displays the positioning of the G8 nations [23] together with a number of other comparator nations outside the G8 which have interesting characteristics. The y-axis in Figure 2.3 represents the proportion of total energy demand that is met from indigenous sources or, to put it another way, the degree of a country's energy autonomy. The x-axis represents the proportion of total energy demand met by fossil fuel sources or the degree of fossil fuel dependence. Each country is plotted against these two axes with the size of the circle representing the absolute size of fossil fuel production in that country providing a measure of the influence of the fossil fuel industry on the economy as a whole (in absolute rather than relative terms). Amongst the G8 countries the following conditions are observed:

- All the nations with the exception of Canada and France have a very high reliance (over 80%) on fossil fuels for their energy needs, i.e. they have high dependency.
- Of these nations only the Russian Federation demonstrates a high level of autonomy with production well in excess of demand. The UK is roughly in balance with the USA, Germany, Italy, and Japan showing increasing degrees of deficit (decreasing autonomy).
- In terms of absolute levels of production, the USA and the Russian Federation are by far the largest producers, followed by the UK. Production in Germany is modest and in Italy and Japan, very small.
- By contrast, France has a significantly lower reliance on fossil fuels (moderate dependency) given the high penetration of nuclear power in its electricity generation mix. Absolute production is however very small and significantly below the level of demand (i.e. autonomy is very low).
- Canada has sizeable production and higher autonomy than its peers as well as demonstrating relatively lower dependency given the strong presence of nuclear and hydro in its electricity generation mix.

In terms of the dynamic characteristics of the UK's energy supply and usage, the trend is currently towards decreasing autonomy as demand continues to increase (albeit relatively slowly), production of North Sea oil and gas decreases and the efforts to replace fossil fuels in the electricity supply industry and elsewhere have yet to have a significant impact.

Since this Thesis is centred on the Scottish energy balance it is interesting to investigate how Scotland would be represented on the chart. Much depends on how the oil from the North Sea is treated and two possible cases are envisaged here as follows:

1. North Sea oil and gas production is attributed to Scotland on a pro-rata basis with the split being based on consumption relative to the rest of the UK; and

2. Production is attributed based on the location of fields being exploited with those deemed to sit within Scottish waters attributable to Scotland, as per the Scottish Government report on energy [24].

In case 1 it can be seen that Scotland is already in a preferential position to the UK as a whole. Its reliance on fossil fuels is found to be lower owing to the increased proportion of nuclear and renewables in the Scottish electricity generation mix. Furthermore, since coal production is more closely in balance with consumption (nearly 90% of demand is met from indigenous sources) the overall autonomy is slightly better. In case 2 Scotland demonstrates the same level of dependency as in case 1 but considerably higher autonomy owing to the much higher production than consumption.

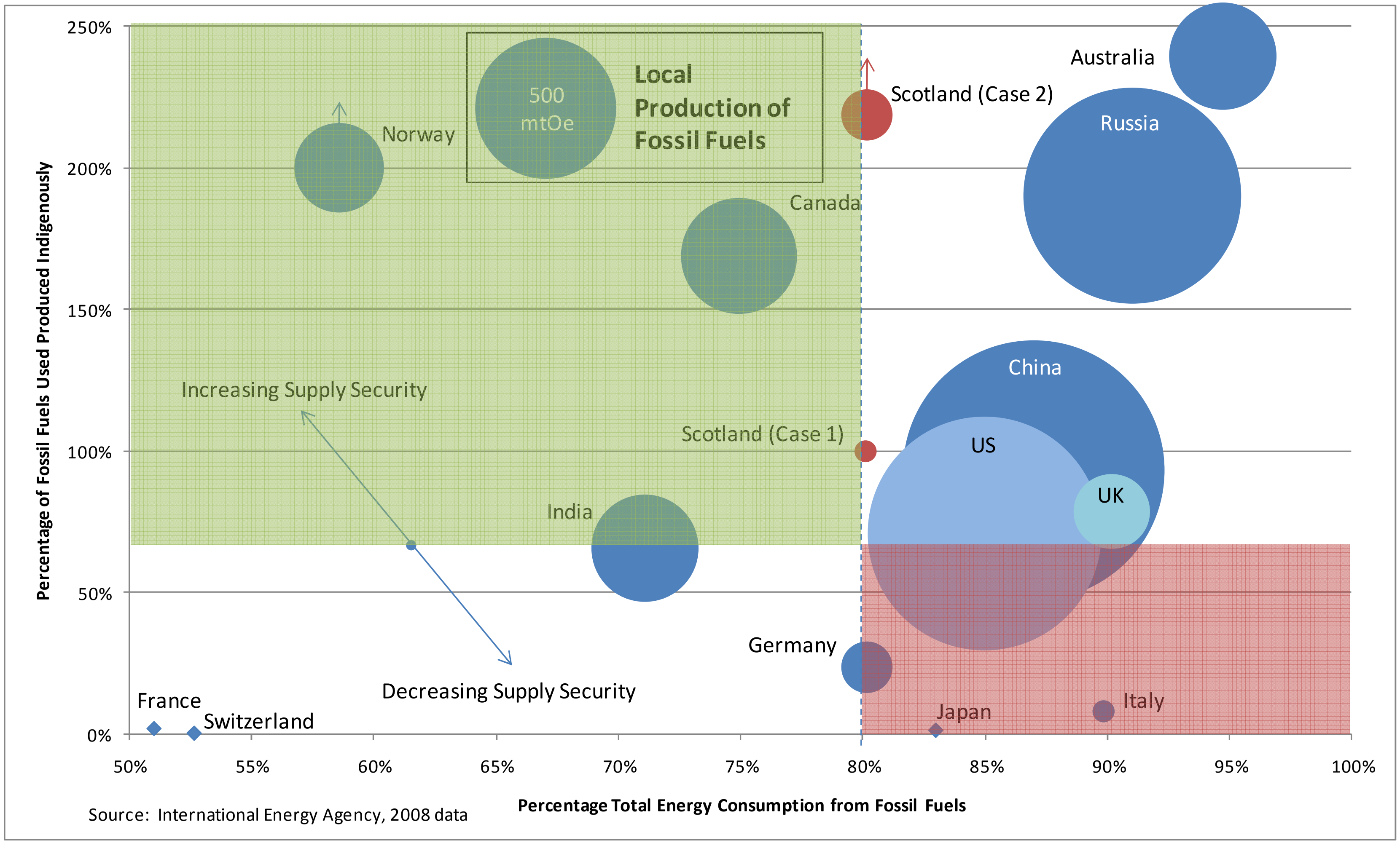



**Figure 2.3 Comparison of Energy Dependency amongst Developed and Major Developing Countries [20]**

### 2.1.2 Other Characteristics

Having established that at an aggregate level the UK is heavily dependent on fossil fuels, in this section certain other aspects of the energy industry that are pertinent to this analysis are reviewed as they have implications for the way in which new energy vectors may be viewed.

#### 2.1.2.1 Relatively monolithic set of energy sources

The provision of energy over at least the last 200 years or so has been remarkably homogeneous in nature. In 1750 water power emerged as a primary driver of the rapidly expanding industrial revolution and this coexisted with biomass used for heating and industrial processes, notably iron-making. From 1800 onwards the advent of the steam engine for stationary and subsequently transportation applications saw a rapid increase in the use of coal, which for a while coexisted with water and biomass but quickly came to replace both. In the latter part of the 19$^{th}$ Century coal was the dominant source of energy for heating, transportation and industrial processes and by 1900 was also being used in the production of electricity and town gas. By 1950 coal was already waning as an energy source for heating, industrial processes and transportation where oil was beginning to play a pivotal role. In electricity generation, coal was still dominant although the emergence of nuclear power was starting to have an impact. Since around 1990, natural gas began to displace both oil and coal in many applications such as heating, power generation and some industrial processes although oil has remained dominant in transportation. Figure 2.4 serves to illustrate the point, showing the relative shares of biomass, coal and oil in the overall energy supply globally. What this chart then attempts to predict is a gradual return to low carbon technologies over the next 100 years which could include sources such as biomass and potentially renewable hydrogen.

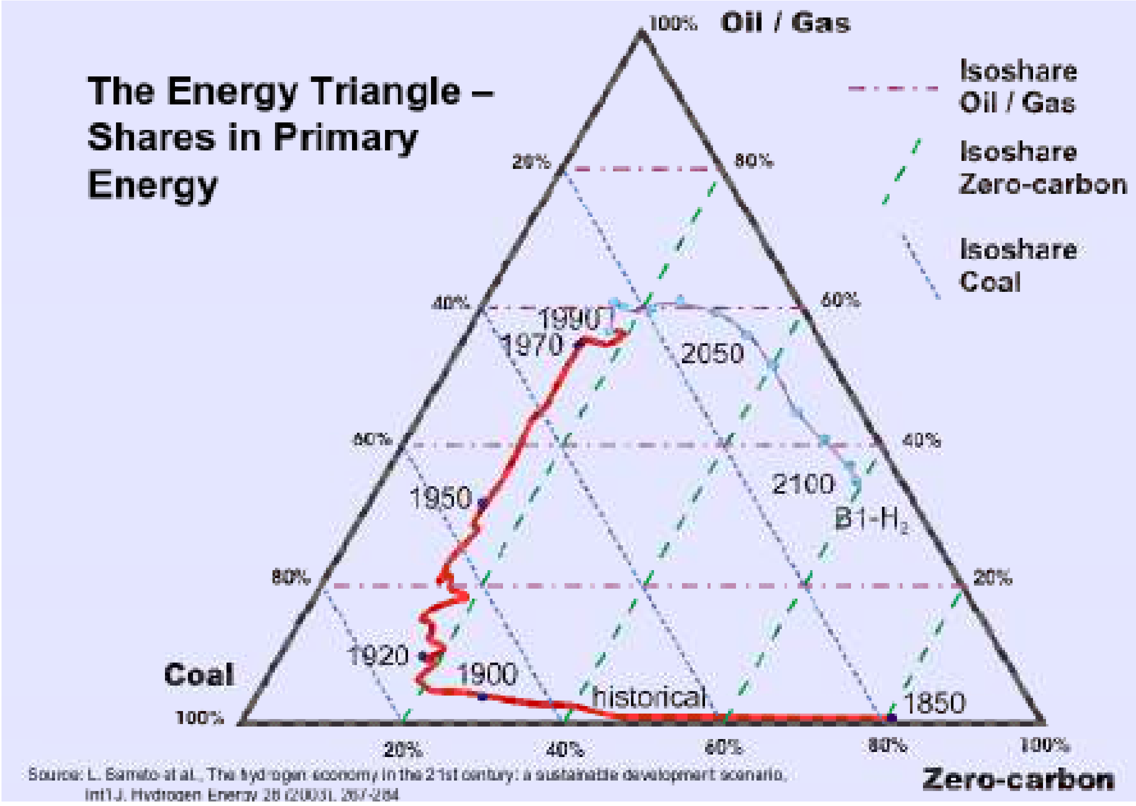



**Figure 2.4 The Energy Triangle: Shares in Primary Energy and Carbon of Different Fuel Types over Time**

#### 2.1.2.2 Centralised delivery

The monolithic nature of energy provision is reflected in the delivery architecture which saw a drive to increasing centralisation until the latter part of the 20$^{th}$ Century [25]. This is true for transportation fuels which rely on highly centralised refining capacity and electricity generation which has been built around large plant connected by an extensive transmission network. The drive towards centralised delivery was predicated primarily on the assumption that the centralised production of petroleum products or electricity would offer the cheapest solution. Consequently, the architecture trended to ever larger plant which has only reversed since 1995 and even then to a limited extent. The societal drive to provide secure energy supplies for all but the most remote locations has also supported the creation of centralised systems for the production and distribution of energy. This requirement has underpinned the current energy architecture providing an inter-connected network of energy production facilities providing security through redundancy. The desire for ubiquitous supply is linked to the requirement for consistent pricing across the entire population and the current architecture provides a roughly consistent cost base for delivery of energy country-wide. Thus there is a real and an imagined relationship between the energy delivery infrastructure and the price to the end user which has favoured centralised production.

#### 2.1.2.3 Relatively firm delineation between energy supply chains

Currently markets for energy remain in “silos”. Regulatory effects on the one hand, and a relative lack of substitutability between different energy sources and vectors on the other, has meant that separate and distinct value chains exist, for example, for the supply of transport fuel and for domestic energy. In the UK for example, virtually 100% of all transport fuel is derived from oil while 82% of all homes are heated by gas providing empirical evidence of non-substitutability [26]. Different companies are involved in the different supply chains each with different financial characteristics and this has resulted in energy suppliers tending to remain within the confines of their existing activities, e.g. BP in oil and gas exploration and production and Scottish Power in electricity generation and distribution, although it is worth noting BP’s interests in alternative energy technologies.

#### 2.1.2.4 Drive to standardisation especially in the transportation market

The drivers are strong within the transportation sector, or at least the relatively price sensitive private passenger car market, to minimise the number of fuels in use. Standardisation in car production was vigorously pursued in order to achieve the benefits of scale. These scale economies were supported by the presence of a homogeneous fuel supply which in the UK was simplified by the removal of the 2- and 4-Star alternatives in 1989 and the subsequent the withdrawal of 4-Star in favour of unleaded in 2000 [27]. While the latter change was driven as much by environmental concerns, these simplifications have allowed the standardisation of many of the fundamentals of vehicle technology although today’s flexible production techniques mean that this driver is not as profound as it once was, potentially supporting the case for a greater fuel diversity in the future [28].

#### 2.1.2.5 Commodity-driven

The prices of fossil fuels demonstrate all the characteristics expected of a commodity with short-run prices acutely reflecting the prevailing supply and demand conditions [29]. The effect of this has been to introduce a high degree of volatility into fuel prices and to decouple price and the underlying costs of production. Demand fluctuates on an intra-year and inter-year basis whereas production cannot necessarily be adjusted immediately in the face of changes in demand thus inducing price volatility. Since the cost targets for alternatives to oil and gas are largely informed by assumptions about the price of oil, understanding these pricing mechanisms becomes important to the current analyses.

## *2.2 Quantifying the Contribution of Energy to the UK Economy*

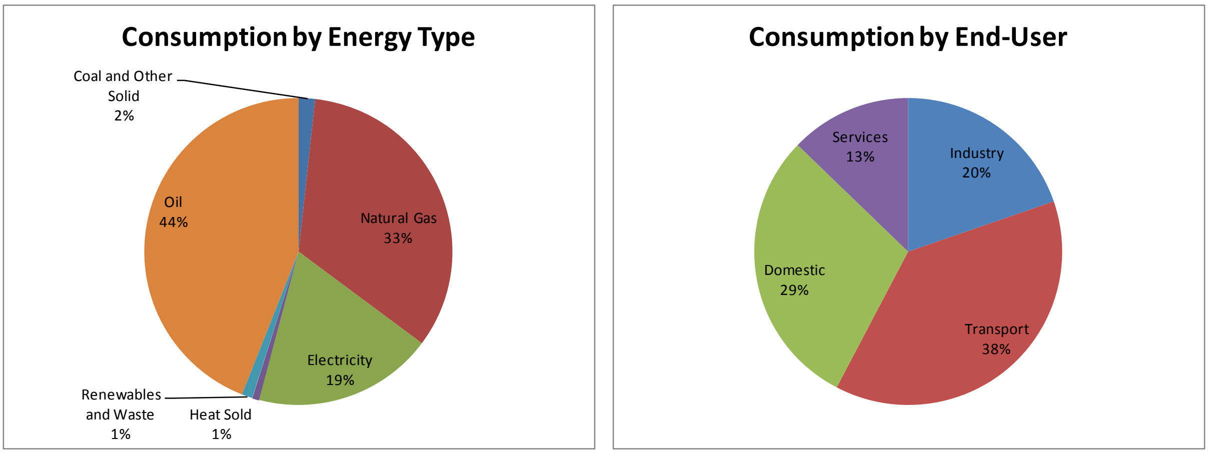
In order to better understand the impact energy has on economic activity and growth in the UK, the following three factors have been analysed:

1. *Total energy spending by UK businesses and individuals* – Defines the size of revenues from the supply of energy available to companies in the sector under current pricing conditions.
2. *GDP attributable to the energy sector* – Calculation of the total contribution to GDP of companies in the energy industry as defined in Section 2.1.
3. *Contribution to UK savings* – Calculates the proportion of the market capitalisation of all UK listed securities represented by energy companies. This provides a measure of the impact that the energy sector has on consumer savings.

The reason for considering the first of these is to understand the impact that changes in the prices of energy might have on economic activity elsewhere. The last two factors demonstrate the impact firstly on GDP and secondly the effect on the economic activity based around the "wealth effect" [30] which relates the level of consumption to the wealth or perceived wealth of the nation.

### 2.2.1 Energy Spend

According to DECC in their 2009 energy statistics [31] (referring to 2008 data) the market value of energy consumed in the UK was £168 billion, equivalent to approximately 12% of GDP. Clearly the size of this spend is a function of the level and distribution of consumption and of the price of energy. The split of energy usage by customer type and primary energy source was previously provided in Figure 2.2 but what this does not demonstrate is the role that electricity plays as an energy vector (or energy carrier as distinguished from a primary energy source) since it only considers primary electricity production from either renewables or nuclear. Figure 2.5 provides a picture of consumption by energy sources, uses and intermediate carriers.




Source: Digest of United Kingdom Energy Statistics 2008, Department for Energy and Climate Change [31]

**Figure 2.5 UK Energy Consumption by Primary and End-User Type**

One interesting aspect of the analysis is the degree of inter-dependence that exists between the pricing of different energy sources and vectors. It has long been established that a correlation exits between the price of oil and that of natural gas [32]. In Continental Europe this relationship has been explicit, where the price of natural gas has been deliberately pegged to that of oil since 1962 [33] but even in liberalised markets the relationship is strong. In the UK, where approximately 37% of electricity is generated from natural gas there also exists a correlation between the wholesale price of electricity and oil which has been well documented by Awerbuch et al [34]. The author's own analyses presented in Section 2.5.6 confirm the fact that the UK energy sector has an extremely high sensitivity to changes in the price of oil and since the price of oil has proven to be highly volatile [35], it has been asserted that this has a negative impact on GDP. While facilities exist for suppliers and consumers to hedge against movements in the price and effectively lock in prices such techniques are imperfect and involve transaction costs. Given the reliance of the UK energy industry on oil either directly or indirectly, this issue is acute and the role that hydrogen might play in reducing the risk associated with oil price volatility will be discussed in more detail in Section 2.5.6.

### 2.2.2 Contribution to GDP

The second methodology applied to measure the size of the energy sector to the UK is to consider its contribution to Gross Domestic Product (GDP). The GDP contributed by the energy sector is calculated by the summation of the GDP of each activity making up the energy sector. As has been described previously, this would include the providers of energy themselves, such as electricity generators but could be extended to encompass the supporting industries as well. GDP is defined in Equation (2.1).

$$GDP = COE + GOS + GMI + Net\,Taxes \tag{2.1}$$

where (all in currency units):

*GDP* = Gross Domestic Product

*COE* = Compensation of Employees (i.e. wages and salaries)

*GOS* = Gross Operating Surplus (roughly equating to profits from incorporated companies)

*GMI* = Gross Mixed Income (roughly profits from non-incorporated companies)

*Net Taxes* = Taxes – Subsidies on Production and Imports

Considering the contribution to GDP from the energy sector results in Equation (2.2).

$$GDP_{Energy} = COE_E + GOS_E + GMI_E + \; Net\,Taxes_E \tag{2.2}$$

The United Kingdom National Accounts (Blue Book) [36] provides annual analyses of UK economic activity on an industry, sector and regional basis. The primary purpose of the accounts is to arrive at a measure of GDP and it may be used to gain insights into the contribution to GDP of particular industries or activities. The Blue Book has been used to assess the total GDP contribution from the energy industry to UK economic activity.

Table 2.1 extracts the key line items from the Blue Book which relate to the energy industry in 2007. The analysis suggests that UK energy activities directly account for approximately 10.6% of GDP. What this does not capture is the wider set of activities that could be considered to be dependent on the energy industry but which would be categorised as industrial. For example, a maker of telemetry equipment which supplies the UK nuclear power industry would be captured under the heading "manufacturing" in the Blue Book and yet it could be thought to form part of the broader UK energy industry. It might be reasonable therefore to assume that the contribution to the UK economy from energy activities is in excess of 10% of total GDP. This is roughly consistent with the figure obtained by considering energy spend and raises the interesting question of what activities might serve to replace declining oil and gas receipts (a large component of energy GDP) and whether there is a growth opportunity associated with increasing the share of indigenous energy activities.

| Activity | Compensation of Employees | Taxes – Subsidies | Gross Operating Surplus + Gross Mixed Income | Gross Value Added | Intermediate Consumption | Total Output |
|---|---|---|---|---|---|---|
| Total UK GDP | | | | | | 1,245,735 |
| Mining & Quarrying | 4,198 | 210 | 27,788 | 32,196 | 13,925 | 46,121 |
| *Mineral Oil Extraction* | | | | *29,127* | *12,598* | *41,725* |
| Electricity, Gas and Water | 5,312 | 1,103 | 14,671 | 21,086 | 52,027 | 73,113 |
| *Electricity and Gas Distribution* | | | | *17,291* | *42,662* | *59,953* |
| Total Energy GDP (excl. Fuel Duty) | | | | | | 101,677 |
| *Percentage Total GDP* | | | | | | *8.2%* |
| Transport, Storage and Communication | 57,285 | 834 | 28,735 | 86,854 | 109,627 | 196,481 |
| *Transport and Storage* | | | | *54,303* | *68,541* | *122,844* |
| *Of which fuel duty / VAT* | | | | | *30,000* | *30,000* |
| Total Energy GDP (incl. Fuel Duty) | | | | 46,418 | 85,260 | 131,677 |
| *Percentage Total GDP* | | | | | | *10.6%* |

*Source: United Kingdom National Accounts (Blue Book)*

*All figures in £million*

*Notes*

1. *Gross Value Added = Compensation of Employees + Net Taxes + Gross Operating Surplus + Gross Mixed Income = GDP before adjustment*
2. *Intermediate Consumption = The cost of raw materials and other inputs that are used up in the production process*
3. *Calculated based on ratio between GVA for sub-group to main group, e.g. IC Mining & Quarrying * (GVA Mineral Oil and Gas Extraction / GVA Mining and Quarrying)*
4. *Equal to duty on fuel*

**Table 2.1 Economic Sources & Uses for UK Energy Activities in 2007**

### 2.2.3 Savings Repository

The final approach taken to measuring the impact of the energy sector on the economic activities of the UK is to consider its relationship to household savings. The first step in this analysis is to consider the contribution of the energy sector to the overall market capitalisation of the UK stock markets. A proportion of household savings is invested in the equity of companies listed on the London Stock Exchange and hence a certain proportion must be invested in energy companies. If it is assumed that the securities of energy companies are held by savers in the same proportion as the energy sector's contribution to the overall market capitalisation of the exchange, a reasonable measure of the impact of industry can be ascertained. It is also interesting to consider the returns attributable to these companies since this provides some measure of the overall impact on wealth that they might have. Thus this section also considers the overall capital returns of the sector in absolute terms as well as dividends payable which when added together provide the overall returns. Table 2.2 provides data relevant to this analysis.

| Sub-Sector | Market Capitalisation (£m) | Proportion Overall Capitalisation | Annualised Capital Return (% 5 years) | Average Dividend Yield (%) | Overall Return |
|---|---|---|---|---|---|
| **Oil & Gas** | | | | | |
| Equipment and Services | 9,713 | 0.59% | | | |
| Oil & Gas Production | 279,923 | 17.07% | 14% | 3% | 17% |
| Oil & Gas (ex BP and Shell) | 60,169 | 3.67% | | | |
| **Utilities** | | | | | |
| Traditional | 43,050 | 2.62% | -22% | 6% | -16% |
| Renewable | 1,697 | 0.10% | -18% | 0% | -18% |
| **Renewable Technologies** | | | | | |
| Bio-Fuels | 99 | 0.01% | -18% | 0% | -18% |
| Other Technologies | 441 | 0.03% | >-50% | 0% | >-50% |
| **Total** | **334,924** | **20.42%** | | | |
| Total (ex BP and Shell) | 115,169 | 7.02% | | | |
| All UK Companies | 1,640,129 | | | | |

*Source: http://www.londonstockexchange.com/statistics/companies-and-issuers/companies-and-issuers.htm*
*2009 data*

**Table 2.2 Analysis of Contribution to the UK Stock Market of the Energy Sector and Returns to Energy Companies**

A look at the equity market capitalisation of companies in the energy sector reveals that roughly 20% of the entire market capitalisation of the exchange is attributable to these activities. That said, roughly 13% of that figure relates to two companies, BP and Shell, which between them have a market capitalisation in excess of £200 billion. Given that the energy sector represents such a significant proportion of the overall market it would seem reasonable to suppose that fluctuations in the values of companies in the sector might have a disproportionate effect on the performance of the market as a whole. While any further investigation of this effect is beyond the scope of this study it would be interesting to understand the potential knock-on effects of such fluctuations.

Considering now the impact on savings, recent studies [37] indicate that roughly 60% of all equities on the LSE Main List are owned by either UK-based institutions or individuals. Table 2.3 shows the breakdown of ownership by category of investor which reveals that, if the proportion of ownership is the same for the energy sector as for the market as a whole, some £184 billion of energy sector equities are owned by, or on behalf of, individual investors (savers).

| **Owners** | **Value (£bn)** | **Percent.** |
|---|---|---|
| Individuals | 43.5 | 13% |
| Insurance Companies | 50.2 | 15% |
| Pension Funds | 43.5 | 13% |
| Investment / Unit Trusts | 13.4 | 4% |
| Other Financial Institutions | 33.5 | 10% |
| *Total "Individual" Savings* | 184.2 | *55%* |
| | | |
| Overseas | 134.0 | 40% |
| Banks | 10.0 | 3% |
| Other | 6.7 | 2% |
| *Total "Non-Individual"* | 150.7 | *45%* |
| | | |
| **Total** | **334.9** | **100%** |

*Source: London Stock Exchange, Office of National Statistics*

**Table 2.3 Ownership of UK Energy Shares by Investor Type**

To put this into context, the National Accounts reveal that total consumer savings reached some £218 billion in 2007, meaning that the value of energy company securities "owned" by individuals is roughly 85% of total gross savings. It might be assumed that fluctuations in the value of these securities would have a significant impact on the wealth of those individuals holding energy securities. This in turn has implications for GDP and wealth creation as a whole.

## 2.3 $CO_2$ Emissions

No discussion of the energy market would be complete without an analysis of the greenhouse gas emissions produced through the consumption of energy. This is especially the case when the purpose of the current research is to investigate the potential impact of substituting fossil fuels with low carbon alternatives. Table 2.4 presents key statistics regarding the UK's greenhouse gas emissions in comparison with the peer group of countries identified in Figure 2.3.

| Country (Rank by total emissions) | Total $CO_2$ Emissions (thousand tonnes per annum) | $CO_2$ Emissions per Capita (tonnes) | $CO_2$ Emissions Intensity (tonnes per US$m of GDP) |
|---|---|---|---|
| China (1) | 6,103,493 | 4.62 | 2,299 |
| USA (2) | 5,752,289 | 18.99 | 436 |
| Russia (3) | 1,564,669 | 10.92 | 1,582 |
| India (4) | 1,510,351 | 1.31 | 1,727 |
| Japan (5) | 1,293,409 | 10.11 | 296 |
| Germany (6) | 805,090 | 9.74 | 276 |
| United Kingdom (7) | 568,520 | 9.40 | 233 |
| Canada (8) | 544,680 | 16.72 | 426 |
| Italy (10) | 474,148 | 8.06 | 254 |
| France (14) | 383,148 | 6.24 | 169 |
| Australia (16) | 372,013 | 18.12 | 493 |
| Switzerland (64) | 41,826 | 5.61 | 108 |
| Norway (67) | 40,220 | 8.61 | 119 |

**Table 2.4 Total $CO_2$ Emissions and Emissions per Capita for Developed and Major Developing Countries**

Figure 2.6 plots each country against the per capita emissions and emissions intensity measures, revealing four groupings: the Low Intensity countries; the High Usage countries; the Low GDP countries; and the Peloton (i.e. the central pack).

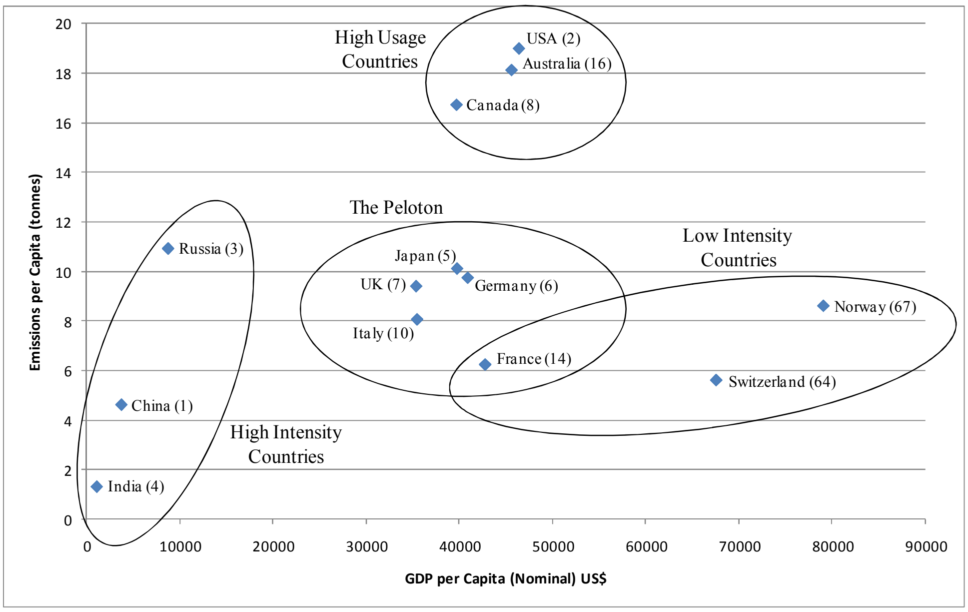



**Figure 2.6 Analysis of per Capita Emissions and GDP for Developed and Major Developing Countries**

*Low Intensity Countries*

Despite high GDP per capita, these countries demonstrate low per capita emissions suggesting a low carbon energy mix and, potentially, relatively lower carbon intensity economic activities.

*High Usage Countries*

These countries have high usage per capita which is only partly explained by higher economic activity. This suggests either a higher carbon content in the energy mix or a reliance on higher carbon intensity economic activities.

*High Intensity Countries*

These countries have high emissions intensity which is explained by the much lower GDP per capita than the other countries in the group. Russia has relatively higher emissions per capita than the other two countries in this grouping which might be explained either by higher reliance on fossil fuels or higher carbon intensity economic activities.

*Peloton Countries*

These sit in the middle, having average levels of emissions intensity and emissions per capita. Note that France has a relatively lower intensity than the other members of the peloton and could perhaps be set alongside the low intensity countries. The UK is part of the peloton.

There has been a steady fall in $CO_2$ emissions in the UK since 1990 as shown in the Figure 2.7 with an overall decline of approximately 10% being observed over the period.

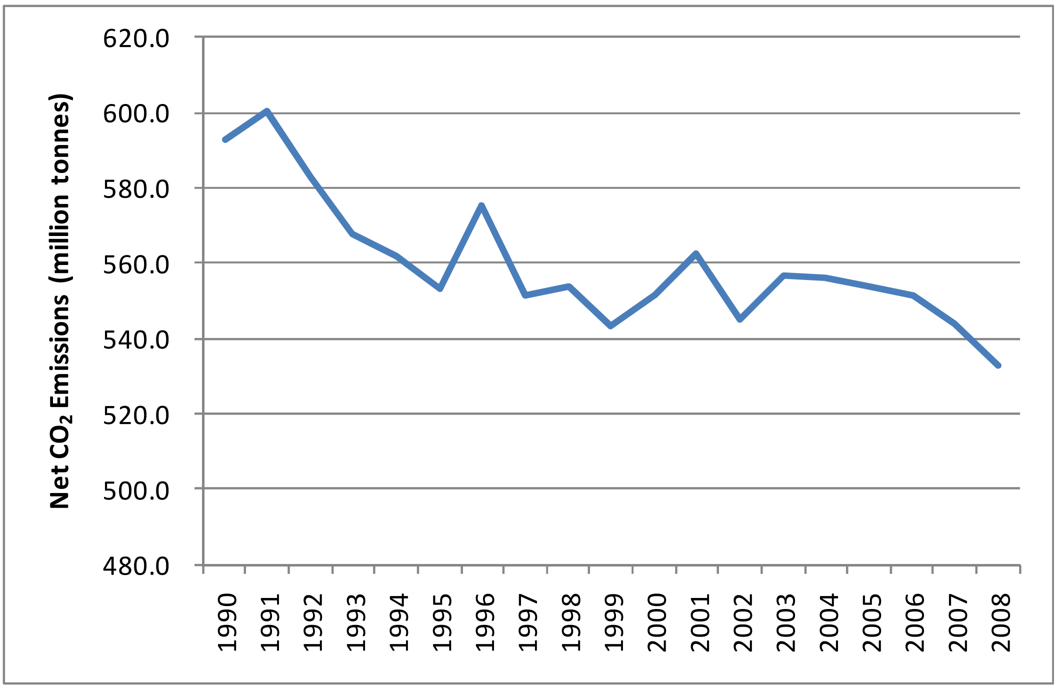



**Figure 2.7 Evolution of Total UK $CO_2$ Emissions Between 1990 and 2008**

The split of carbon dioxide emissions according to end use is presented in Figure 2.8.

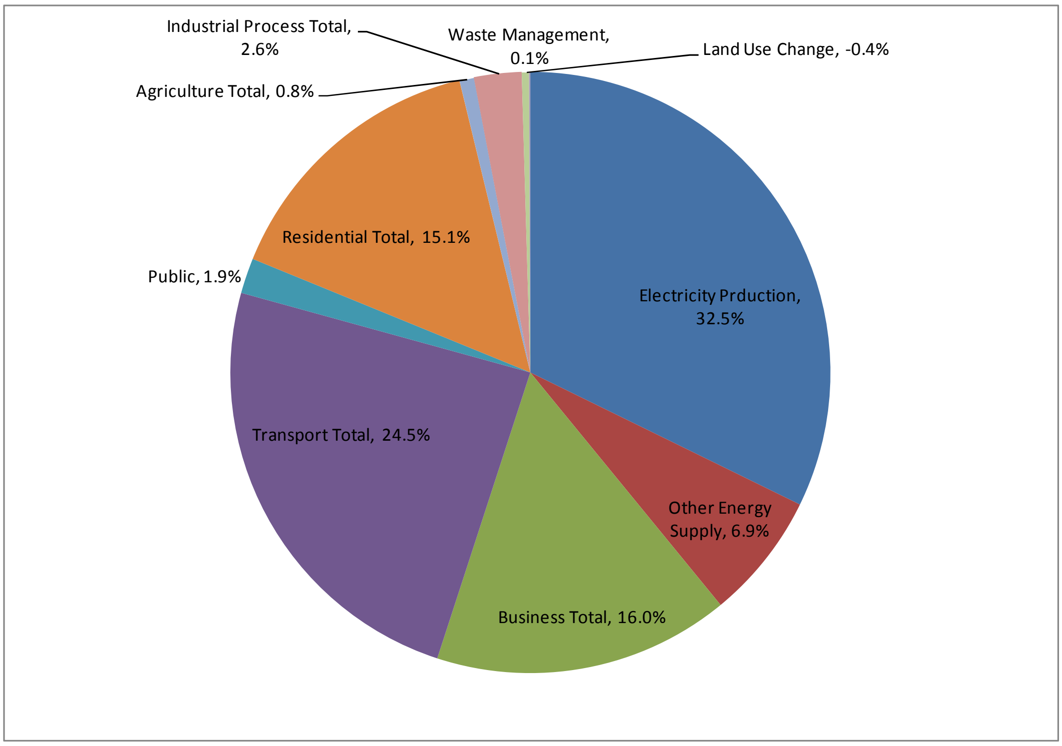



**Figure 2.8 Total UK $CO_2$ Emissions by End Use**

Of the main contributors to $CO_2$, electricity generation represents approximately one third, residential and business emissions sharing equally another third and transport about one quarter. The rest is mainly attributable to other energy supply (e.g. refining activities) and industrial activities.

## *2.4 Government Intervention to Shape the Energy Market*

The energy markets have for a considerable period of time been the subject of government policy and regulation. The post-war period in the UK saw the nationalisation of significant parts of the energy market [38] including the electricity supply industry which until that time had been characterised by a collection of independent local private and municipal suppliers. Subsequently, in the latter part of the 20$^{th}$ Century, much of the energy industry in the UK was moved back into private ownership through the programmes of privatisation. Whilst initially subject to significant regulation, at least in the electricity and gas supply industries, these controls were gradually dismantled in favour of liberalised markets. Today the UK enjoys one of the least regulated energy markets but the level of government intervention has been gradually increasing again as it seeks to address the need for lower carbon emissions and energy security. The key elements of *future* policy for emissions reduction are highlighted in Figure 2.9. These anticipated reductions reflect national and international level commitments on climate change the principal among which are listed below.

- The UK's commitment to the Kyoto Protocol which led to the enactment of the Climate Change Act requiring an 80% reduction in carbon emissions below 1990 levels by 2050.
- The UK is signatory to the EU Renewable Energy Directive which requires 20% of energy across EU to be supplied from renewable sources, with a lower commitment of 15% for the UK. In addition, 10% of transport energy must be obtained from renewable sources and a 6% reduction in carbon emissions from road transport must be achieved. The UK government estimates that in order to meet these overall objectives it will need to supply 30% of electricity from renewable sources.
- Directives on energy efficiency and services provide mechanisms and targets for the built environment while the Fuel Quality Directive provides a means to monitor, and ultimately reduce, emissions from road transport.
- The Scottish Government meanwhile has a commitment to supply 50% of electricity from renewables by 2050 (with an interim target of 31% in 2020), 11% of heat from renewable by 2020 and deliver an 80% carbon reduction by 2050 (42% interim target in 2020).

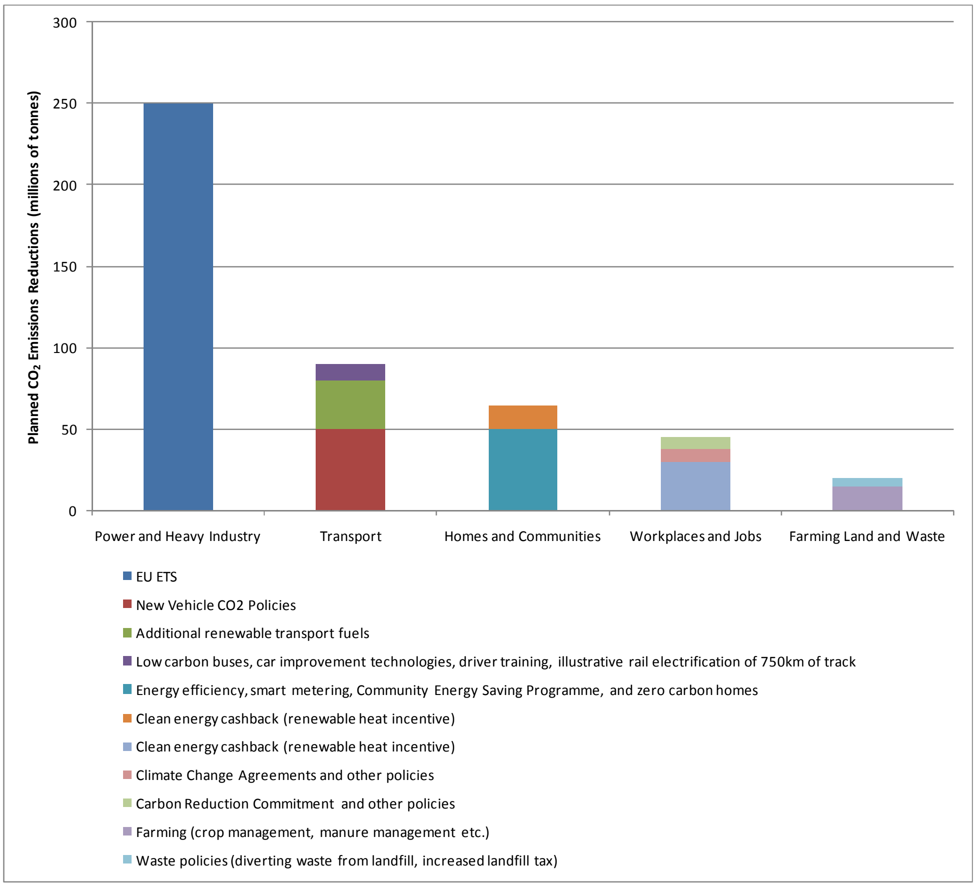
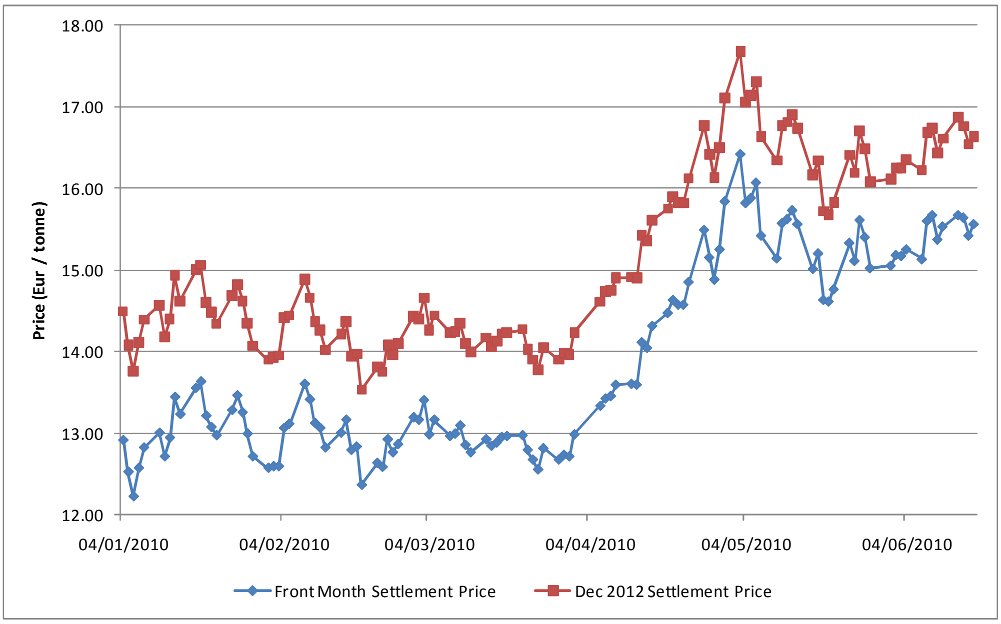



**Figure 2.9 UK Planned $CO_2$ Reduction by Key Policy and Demand Type**

Policy measures can have either a more general impact across different energy types or be directed specifically to particular energies. For example, the climate change levy is a more general policy to reduce overall demand whereas the Renewable Obligation focuses specifically on the renewable electricity commitments. Policy, therefore, in some sense reflect the different aspects of political commitment listed above. To an extent, the analysis of policy measures also reflects the delineation and while this may be satisfactory if the energy paradigm remains fixed, in the face of disruptive technologies such an approach may have limitations. To put it another way, policies are designed to select between currently competing technologies whereas they should perhaps reflect non-competing ones too. Biofuel is a direct competitor to petrol and diesel but in a new paradigm electricity could also be a direct or indirect competitor through battery electric vehicles (BEVs) or hydrogen fuel cell vehicles (FCVs). For this reason, the author's model attempts to address the impact of measures across multiple technologies but with a clear focus on electricity and hydrogen. Currently, there are four key areas of legislation which seek to achieve early emissions reductions which are described in the following sections.

### 2.4.1 Emissions Trading

According to the UK Low Carbon Transition Plan [39], the best way of incentivising the most cost-effective (note the reference once again to cost-effectiveness) mix of low carbon technologies is to put a limit or 'cap' on emissions. Since 2005, the European Union Emissions Trading System (EU ETS) has set a declining cap on emissions from the large industrial sectors, including power. The EU ETS is the first multilateral carbon trading system of its scale, anywhere in the world, and is expected to account for over 65% of the emissions savings in Europe by 2020. It is expected to reduce Europe's emissions by around 500 million tonnes in 2020, and the UK Government hopes to make carbon savings of 250 mt$CO_2$ through this means. Figure 2.10 provides the front month and December 2012 settlement price for EUA Carbon Futures contracts since the start of 2010.




*Source: European Climate Exchange (www.ecx.eu) [40]*
*Note: Front month refers to the futures contract month with an expiration date closest to the current date*

**Figure 2.10 Evolution of EUA Front Month December 2012 Futures Settlement Price Since Start 2010**

It should be noted that despite the heavy reliance on the ETS to deliver the carbon savings anticipated in the Low Carbon Transition Plan, the price of carbon remains at a much lower level than would be required to achieve the plan [41].

### 2.4.2 Demand-Side Measures

These are measures designed to decrease the demand for energy in general and high carbon energy in particular.

#### 2.4.2.1 Climate Change Levy

The Climate Change Levy (CCL) [42] is an energy tax, the aim of which is to encourage businesses to use energy more efficiently. It is charged on energy supplied to business and the public sector, but not, for example, on renewables or on good quality combined heat and power plants. Fuel supplied for electricity generation and most fuels supplied for transport are also excluded. The tax is currently set at £1.50 per MWh of energy consumed for natural gas, £4.30 for electricity and £9.60 for oil. In the case of natural gas, say, this translates into a price per tonne of carbon emitted of £7.60 per tonne, approximately half the EAU price.

#### 2.4.2.2 Incentive schemes

Various schemes exist to incentivise businesses and consumers to implement energy savings including the Climate Change Agreements (CCA) [43]. These were established to mitigate the impact of the Levy on the competitiveness of energy intensive industry, whilst also securing uptake of energy efficiency opportunities. CCAs are voluntary agreements between government and industry that enable eligible energy intensive businesses to obtain an 80% discount from the CCL in return for meeting challenging, but cost effective, energy efficiency or carbon saving targets. Other measures include the domestic boiler scrappage scheme [44] to encourage homeowners to replace old central heating boilers.

### 2.4.3 Supply-Side Measures

#### 2.4.3.1 Renewable Obligation / Renewable Transport Fuel Obligation

The Renewable Obligation (RO) [45] provides a financial incentive to invest in renewables by placing an obligation on electricity suppliers to source a certain proportion of the electricity they sell to customers from renewable sources. Renewable energy generators receive Certificates, known as Renewables Obligation Certificates (ROCs) for the renewable electricity they produce, and can then sell these (if they have a surplus) to other electricity suppliers, who use them to meet their obligations. They demonstrate this by submitting the ROCs they have bought. If they are unable to present ROCs for the whole of the specified amount of electricity, they have to pay a penalty, the buyout price (see Table 2.5). These payments are redistributed to suppliers who did present ROCs. It is this redistribution that provides the incentive for suppliers to present ROCs rather than simply paying the buy-out price. ROCs can be sold with or without the electricity they represent, meaning that they provide generators with financial support above what they receive from selling their electricity in the wholesale market.

| Renewable Obligation period | Percentage of Supply | Buyout Price (£/MWh) | Traded Price (ROC in £/MWh) |
|---|---|---|---|
| 2002 / 3 | 3.0 | 30.00 | 47.12 – 47.46 |
| 2003 / 4 | 4.3 | 30.51 | 45.93 – 48.76 |
| 2004 / 5 | 4.9 | 31.69 | 46.12 – 52.07 |
| 2005 / 6 | 5.5 | 32.33 | 38.42 – 46.07 |
| 2006 / 7 | 6.7 | 33.24 | 40.62 – 46.17 |
| 2007 / 8 | 7.9 | 34.30 | 47.51 – 49.95 |
| 2008 / 9 | 9.1 | 35.76 | 51.34 – 53.27 |
| 2009 / 10 | 9.7 | 37.19 | 46.25 – 52.90 |
| 2010 / 11 | 11.1 | 36.99 | NA |

Source: NPFA

**Table 2.5 Renewable Obligation: Amount of Obligation, Buyout Price and Auction Price by Period**

Different technologies receive different numbers of ROCs, to account for differences in technology costs under modifications to the Renewable Obligation enacted in 2009 [46]. The Scottish Government made its own additions to the Renewable Obligation which provided even stronger incentives to newer marine technologies, offering 1.5 ROCs to offshore wind (as with the rest of the UK), 3 ROCs to tidal power and 5 ROCs to wave power [47].

In similar vein, the Renewable Transport Fuel Obligation (RTFO) [48] requires suppliers of transport fuel to ensure a proportion of transport fuel sold is bio fuel; suppliers failing to meet the requirement must purchase Transport Obligation Certificates (TOC) in the same way as for the RO. The current obligation is 5% and the buyout price 15 pence per litre; the TOC currently trades below the buyout price. In addition to the RTFO benefit, fuel duty on qualifying low carbon fuels is 20 pence per litre lower than for conventional fuels providing a total benefit to biofuels over fossil fuels of 35 pence per litre. While hydrogen is not a qualifying fuel under the RTFO, which is aimed principally, if not solely, at encouraging the use of bio-fuels, it has been assumed in the author's model that hydrogen does receive such a benefit. The logic of this is that it seems probable that support will become available to a variety of low and zero-carbon fuels as these become more viable from a technological point of view.

#### 2.4.3.2 Feed-in Tariff / Renewable Heat Incentive

The feed-in tariff (FIT) [49] aimed at individuals or small independent power producers guarantees a minimum tariff for electricity used or (at a higher tariff) sold to the grid. A similar "cash-back" scheme exists for those business or domestic consumers producing their own renewable heat.

### 2.4.4 Other Measures

#### 2.4.4.1 Grant funding

As a means to stimulate and support investment in renewable energy technologies, the government has put in place various research grant programmes designed to encourage the development and large-scale testing of low-carbon technologies. Programmes include Offshore Wind, Marine, Ultra Low Carbon Vehicles and Smart Electrical Grid (see [39]).

#### 2.4.4.2 "Commercial" funding

The Government-funded Carbon Trust [50] has a mission to cut carbon emissions by providing business and the public sector with expert advice, finance (including interest free loans) and accreditation, and by stimulating demand for low carbon products and services. The European Investment Bank has programmes of "soft loans" for various energy investments together with an associated venture capital activity. The UK meanwhile in 2010 announced the establishment of a green investment bank as a means to providing liquidity and lowering the cost of capital to investors.

## 2.5 Addressing the UK's Energy Challenges through the Application of Hydrogen Energy

As was discussed in Section 1.5, the direction of hydrogen to the energy sector has a number of potential benefits when set against the picture described in the preceding sections of Chapter 2. In particular, hydrogen can help to address:

1. *Greenhouse gas emissions reduction* – hydrogen fuel is zero emissions at the point of use and has the potential to be completely zero emissions from the point of production;

2. *Energy security* – hydrogen has the potential to be produced from indigenous renewable resources and hence address issues over security of supply; and

3. *Industrial renewal* – energy represents a significant proportion of GDP and as established industries in the oil and gas sector, for example, begin to decline hydrogen production and applications could provide replacement economic activities.

In order to understand in more detail how hydrogen could contribute to the energy picture of the UK in general and Scotland in particular, the characteristics and use of hydrogen as a fuel are described in the following sections.

### 2.5.1 Hydrogen and its Application as an Energy Vector

Hydrogen is the first element in the periodic table. At room temperature it exists as a gas but since the element is highly reactive it tends to form compounds with the other matter around it and as such rarely exists alone in nature. It is the most ubiquitous element and has considerable merit for use as a carrier of energy. While hydrogen is already used extensively in industrial processes, it has for a considerable period of time been considered as a potential fuel given its ubiquity and the fact that it has the highest energy density per unit of mass of any known element. As it does not typically exist alone in nature, hydrogen is not a fuel in the way hydrocarbons are understood to be fuels since before it can be used it must be synthesised from other compounds, for example existing hydrocarbons or water. In this sense it can be thought of as having similarities with electricity. Table 2.6 provides some relevant data relating to hydrogen particularly in respect of its application as a fuel together with equivalent data for common existing fuels.

| | **Hydrogen** | **Natural Gas** | **Petrol** | **Coal** |
|---|---|---|---|---|
| **Lower Heating Value** | 120.1 MJ / kg (33.4 kWh / kg) | 38.1 MJ / kg (10.6 kWh / kg | 42.5 MJ / kg (11.8 kWh / kg) | 33.3 MJ / kg (9.25 kWh / kg) |
| **Density** | 0.09 kg / $m^3$ (at STP) | 0.7 – 0.9 kg / $m^3$ (at STP) | 737.22 kg / $m^3$ | 1,100 – 1,500 kg / $m^3$ |
| **Atomic Weight** | 2 g / mol | 16 g / mol | 114 g / mol | 12 g / mol (carbon part) |
| **Appearance** | Colourless, odourless gas | Colourless, odourless gas | Colourless liquid | Black or brown solid |
| **Boiling Point** | -252.9°C | -161.5°C | 95.0°C | NA |
| **Flammability Limits (in air)** | 4-74% | 5.3-15% | 1.4-7.6% | NA |
| **Explosion Limits (in air)** | 18.3-59.0% | 5.7-14% | 1.1-3.3% | NA |

*Source: Hydrogen Analysis Resource Center [51]*

**Table 2.6 Physical Properties of Hydrogen Relative to Other Fuels**

The first thing to note from the data in Table 2.6 is that although hydrogen's energy content by mass is very high compared with other fuels, its density is extremely low and consequently the energy content by volume compares unfavourably with other fuels unless it is either highly compressed or liquefied. The second thing to note is that while the majority of fuels either exist in liquid or solid form or can relatively easily be converted into liquid form, hydrogen has a boiling point close to absolute zero meaning that liquefying it and maintaining it as a liquid requires considerable input energy. It is also worth noting that separating hydrogen from the compounds in which it naturally occurs also requires significant amounts of energy leading to the low production efficiencies referred to in Table 2.7 below.

Despite the shortcomings described in the previous paragraph, hydrogen has much to commend it especially in the context of depleting fossil fuel reserves, concerns over supply security and efforts to reduce greenhouse gases and other airborne emissions. When combusted or used in a chemical cell to create useful work (or exergy), the only by-product is water as the hydrogen reacts with oxygen in the air. Thus hydrogen produces no harmful emissions at the point of use unlike hydrocarbons, which produce both air pollutants such as $NO_x$ and significant quantities of greenhouse gases such as $CO_2$. Consequently hydrogen is often referred to as a clean fuel even though the production of it may involve the production of pollutants if, for example, it is produced from hydro-carbons. However, if hydrogen is produced through the electrolysis of water and if the electricity used in the process is from renewable sources then no pollutants are emitted during the production process. In addition, it is thought that hydrogen could be produced from "brown" sources and the carbon captured and sequestered. Hydrogen therefore has the capacity to be a fuel that is completely free from harmful emissions and as such is perceived as having the potential to significantly assist in the reduction of greenhouse gas emissions. What is more hydrogen is not depletable in the same way as fossil fuels and can in theory be produced locally in any region of the world. Consequently it is also perceived as having the potential to offer greater fuel security as well as protection against increasing fossil fuel prices and price volatility. Table 2.7 summarises the key benefits and challenges associated with the use of hydrogen as a fuel.

| Benefits over Existing Fuels | Challenges |
|---|---|
| ➢ Greenhouse gas emission and air pollutant free at point of use<br>➢ Potentially emissions free at point of production if renewable electricity used<br>➢ High energy density by mass means low stored mass (although "packaging" can have significant mass)<br>➢ High energy conversion efficiency when used in conjunction with fuel cells (typically in the range 50 – 70% [52]) | ➢ Very low energy density by volume at STP makes storage in sufficient quantities a challenge especially in non-stationary applications<br>➢ Production efficiency relatively low (typically 45 – 60% [53])<br>➢ Energy used in "packaging" either as compressed gas or liquid is significant adversely affecting overall system efficiency |

**Table 2.7 Analysis of Key Benefits of and Challenges to the Use of Hydrogen as a Fuel**

### 2.5.2 Fuel Cells

The benefits of hydrogen energy presented in Table 2.7 are particularly apparent when considered in conjunction with the introduction of fuel cells into the energy value chain. Fuel cells present the opportunity to convert chemical energy into exergy much more efficiently than in current devices and therefore a discussion of hydrogen energy would be incomplete without an examination of the role of fuel cells in the proposed "hydrogen economy". While a detailed discussion of the characteristics and variants of fuel cells is beyond the scope of this Thesis, a brief description of the main types, applications and key benefits of fuel cells is required in order to put the whole sector into context. The development of the fuel cell is attributed to Sir William Grove who as long ago as 1839 demonstrated that if hydrogen and oxygen were introduced into an electrolysis cell a direct electric current would be generated between the anode and the cathode of the cell. As the fuel cell converts energy directly from its chemical form into electricity, the process is much more efficient than most thermal / mechanical processes (potentially 50 – 60% as compared with 25 – 30% for thermal / mechanical [54]). Since that initial discovery numerous different types of fuel cell have been developed but all follow the same basic principles. The main types of fuel cell are described in Table 2.8.

| Fuel Cell Type | Common Electrolyte | Operating Temp. | System Output | Electrical Efficiency | Combined Heat and Power Efficiency | Applications | Advantages |
|---|---|---|---|---|---|---|---|
| **Polymer Electrolyte Membrane (PEM)** | Solid organic polymer poly-perfluorosulfonic acid | 50 – 100°C | <1kW – 250kW | 53-58% (transport) | 25-35% (stationary) | • Backup power<br>• Portable power<br>• Small distributed generation<br>• Transportation<br>• Specialty vehicles | • Solid electrolyte reduces corrosion & electrolyte management problems<br>• Low temperature<br>• Quick start-up |
| **Alkaline (AFC)** | Aqueous solution of potassium hydroxide soaked in a matrix | 90 – 100°C | 10kW – 100kW | 60% | >80% (low-grade waste heat) | • Military<br>• Space | • Cathode reaction faster in alkaline electrolyte, leads to higher performance<br>• Can use a variety of catalysts |
| **Phosphoric Acid (PAFC)** | Liquid phosphoric acid soaked in a matrix | 150 – 200°C | 50kW – 1MW (250kW module typical) | >40% | >85% | • Distributed generation | • Higher overall efficiency with CHP<br>• Increased tolerance to impurities in hydrogen |
| **Molten Carbonate (MCFC)** | Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix | 600 – 700°C | <1kW – 1MW (250kW module typical) | 45-47% | >80% | • Electric utility<br>• Large distributed generation | • High efficiency<br>• Fuel flexibility<br>• Can use a variety of catalysts<br>• Suitable for CHP |
| **Solid Oxide (SOFC)** | Yttria stabilized zirconia | 600 – 1000°C | <1kW – 3MW | 35-43% | <90% | • Auxiliary power<br>• Electric utility<br>• Large distributed generation | • High efficiency<br>• Fuel flexibility<br>• Can use a variety of catalysts<br>• Solid electrolyte reduces electrolyte management problems<br>• Suitable for CHP<br>• Hybrid/GT cycle |

*Source: US Department of Energy [55]*

**Table 2.8 Comparative Analysis of the Characteristics of Different Fuel Cell Types**

In addition to the greater energy conversion efficiency observed, the characteristics of fuel cells also lend themselves to their inclusion in combined cycles. As can be seen from Table 2.8, many fuel cells operate at temperatures of between 50 and 200 degrees Celsius which is an appropriate range for many heating applications. By contrast, the combustion of hydrocarbons, in central heating boilers, for example, generates temperatures of around 1,000 degrees Celsius, far higher than is required for space or water heating and thus this temperature must be reduced to a usable level by heat exchange processes before it can be used. It is thought that if fuel cells, which generate temperatures in the appropriate range, are utilised in combined cycles yet higher efficiencies can be achieved as Table 2.8 shows. Since the energy conversion process is so efficient why have fuel cells failed to be deployed in anything other than niche applications? Two principal issues with the fuel cells themselves account for this apparent paradox.

1. The first is that the cost of fuel cells is currently considered prohibitive for most applications. Fuel cells are often built from expensive components, including platinum as a catalyst, for example, and since they must be constructed to form "stacks" in a process which has yet to be mechanised on any scale, manufacturing costs remain high [56]. At the same time, the nature of the construction of fuel cells mean that lifetime [56] and, to a lesser extent reliability have proved a challenge when compared with established technologies despite the absence of moving parts. These factors result in higher operation and maintenance costs which combined with the high capital cost make the economics of fuel cells dubious in all but the most specialist applications.

2. The second factor is the power to weight ratio which is relatively low compared to existing technologies; the power density of fuel cells has yet to exceed 500W / kg [57] whereas high performance internal combustion engine, for example, can achieve as high as 7.5kW / kg [58]. While in some stationary applications weight is not a particular issue, in non-stationary uses such as transportation it is of greater importance. Poorer power to weight ratio could result in the energy conversion efficiency gains being eroded, weakening one of the key benefits of

the technology. Nevertheless, as research [54] and empirical data [59] has shown, real efficiency benefits over existing technologies can be achieved.

Finally, another key factor which has impeded the introduction of hydrogen and fuel cells is the issue of production and storage. It is generally acknowledged that the costs of producing fuel cells will reduce through learning effects and that reliability and lifetime could similarly be increased if the production volumes increased. Significant increases in fuel cell durability have been achieved already [60] which tends to support this view and continued improvements are expected over time. However one key obstacle remains – how to improve the efficiency of hydrogen production, storage and transportation so that the benefits of greater energy conversion efficiency are not completely lost?

### 2.5.3 Methods of Hydrogen Production, Storage and Transport

While high energy conversion efficiencies are theoretically achievable in fuel cells, the process of producing hydrogen, "packaging" it and then storing and transporting it is currently fairly energy intensive. If the process of converting chemical energy into electricity and heat in a combined cycle fuel cell system is around 70% efficient [52], the process of generating and packaging hydrogen is unlikely to be more than 60% efficient [53]. This implies a combined efficiency of 42% which although significantly higher than is currently achieved by open cycle thermal machines is only comparable with existing combined cycle processes [61].

As was previously noted, hydrogen can be produced from a number of sources and through a number of different methods. The relative stage of development of different methods is summarised in Table 2.9. Currently the cheapest method of producing hydrogen is steam methane reforming but since this relies on a fossil fuel as its raw input hydrogen produced in this way only partially addresses the challenges of greenhouse gas emissions and supply security. Electrolysis has the potential to deliver 100% carbon free hydrogen if sufficient indigenous zero carbon electricity generating capacity exists but is currently relatively costly.

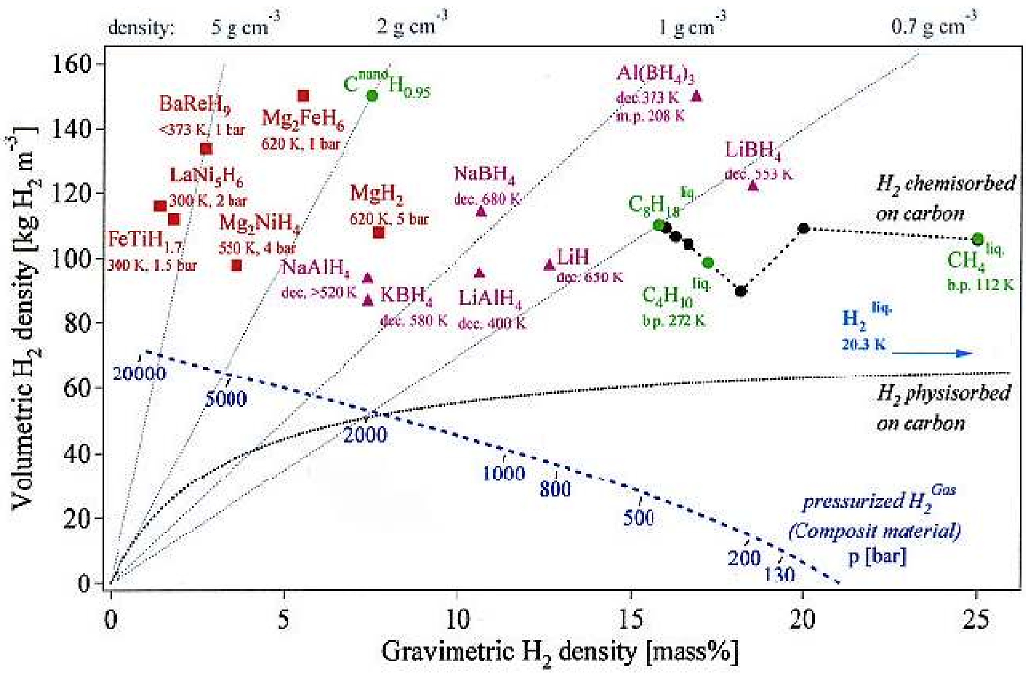
| Technology | Feed stock | Efficiency | Maturity |
|---|---|---|---|
| Steam reforming | Hydrocarbons | 70–85%[a] | Commercial |
| Partial oxidation | Hydrocarbons | 60–75%[a] | Commercial |
| Autothermal reforming | Hydrocarbons | 60–75%[a] | Near term |
| Plasma reforming | Hydrocarbons | 9–85%[b] | Long term |
| Aqueous phase reforming | Carbohydrates | 35–55%[a] | Med. term |
| Ammonia reforming | Ammonia | NA | Near term |
| Biomass gasification | Biomass | 35–50%[a] | Commercial |
| Photolysis | Sunlight + water | 0.5%[c] | Long term |
| Dark fermentation | Biomass | 60–80%[d] | Long term |
| Photo fermentation | Biomass + sunlight | 0.1%[e] | Long term |
| Microbial electrolysis cells | Biomass + electricity | 78%[f] | Long term |
| Alkaline electrolyser | H2O + electricity | 50–60%[g] | Commercial |
| PEM electrolyser | H2O + electricity | 55–70%[g] | Near term |
| Solid oxide electrolysis cells | H2O + electricity + heat | 40–60%[h] | Med. Term |
| Thermochemical water splitting | H2O + heat | NA | Long term |
| Photoelectrochemical water splitting | H2O + sunlight | 12.4%[i] | Long term |

NA = not available.
a Thermal efficiency, based on the higher heating values.
b Does not include hydrogen purification.
c Solar to hydrogen via water splitting and does not include hydrogen purification.
d Percent of 4 mol H2 per mole glucose theoretical maximum.
e Solar to hydrogen via organic materials and does not include hydrogen purification.
f Overall energy efficiency including the applied voltage and energy in the substrate. It does not include hydrogen purification.
g Lower heating value of hydrogen produced divided by the electrical energy to the electrolysis cell.
h High temperature electrolysis efficiency is dependent on the temperature the electrolyser operates at and the efficiency of the thermal energy source. For example, SOEC operating from advanced high temperature nuclear reactors may be able to achieve up to 60% efficiency. If thermal energy input is ignored, efficiencies up to 90% have been reported.
i Solar to hydrogen via water splitting and does not include hydrogen purification.

Source: Holladay et al [62]

**Table 2.9 Comparative Analysis of Alternative Methods of Hydrogen Production**

Importantly, if electrolysis is used in combination with renewable electricity generation it also serves to address the security of supply issue and could go some way to addressing the price volatility issue as well, as described in more detail in Section 2.5.7. Finally, the novel methods mentioned are not yet at a point where they can be exploited commercially but do offer potentially exciting future opportunities for development. Once hydrogen has been produced it will often be stored until needed either at the point of production or at the point of use. In common with other gases, hydrogen can be stored either in compressed gas or liquid form although in either instance key issues exist which have been alluded to previously. Since hydrogen has an extremely low density, storing it as a gas in sufficient quantities in a manageable volume requires it to be highly pressurised, typically >200 bar (although it should be noted that much bulk storage where storage size is not an issue is at <200bar). If it is stored as a liquid on the other hand it must be cooled to an extremely low temperature (-253°C) and maintained at that temperature until used. Both methods require a significant energy input either to compress or liquefy the gas (typically 15% of energy stored for compression and at least 30% for liquefaction [53]) and the package within which the gas is housed is potentially large in size (implying an ultimately low energy to weight ratio overall) and costly to manufacture. In consequence, other methods of storage have been investigated notably metal hydride storage vessels in which the hydrogen is in effect trapped in the atomic structure of the hydride material. The hydrogen is usually stored in or liberated from the hydride through changes in temperature or pressure but it typically only requires a relatively modest amount of energy input to achieve this roughly 10 – 15% of LHV of hydrogen [63]. However, currently the storage density of these methods make them uncompetitive as can be seen from Figure 2.11 which provides an overview of the different storage methods plotted along mass and volume storage density axes. Although not shown in Figure 2.11, the costs are also likely to be prohibitive at this stage of development.




*Source: Schlapbach and Züttel, Nature, 2001 [64]*

**Figure 2.11 Volumetric and Gravimetric Densities of Different Hydrogen Storage Media Together with Operating Pressures and Temperatures**

Finally, in terms of transporting hydrogen from the point of production to the point of use, many of the same issues are apparent as with storage. If hydrogen is to be transported by tanker, as with current transport fuels for example, then the issues are very similar to those just described. If on the other hand the gas is to be transported in a pipeline, for domestic or industrial use, for example, other issues present themselves. The small molecule size of hydrogen increases the likelihood of leaks [65] and requires special measures to be taken to prevent these. Furthermore there are potential issues with embrittlement of metals [65] when they come into contact with hydrogen which might affect the lifetime of equipment used to store and transport hydrogen. At least one study has been carried out [65] to investigate to the extent to which hydrogen could be transported in existing natural gas pipelines either in pure form or in a mixture with natural gas (including the specific patented $H_2$ / NG mixture referred as Hythane [66]). These highlight a number of technical encumbrances but suggest that such an approach might be feasible with some modifications to the pipelines themselves. Transport by pipeline in liquid form has also been implemented in the aerospace sector but the technical issues for larger systems are considerable.

### 2.5.4 Applications for Hydrogen Energy

In general, hydrogen can be used as a fuel in any application where fossil fuels are used today, although significant technical and economic issues remain with respect to the practical use of hydrogen as an alternative fuel. Furthermore, it is more suitable in some applications than others and is currently competing with a variety of alternative technologies to address the triple challenges of energy security, energy price volatility and emissions reduction. When considering the relative strengths of hydrogen as a fuel in particular applications, it is important to consider it not in isolation but also in comparison to other technologies. In reality, the author's model was built specifically to investigate the potential market for hydrogen energy production and consequently the alternative technology sets are considered in significant detail. This is not to say that these solutions are mutually exclusive or that the list of possible solutions stated is exhaustive but this analysis serves to identify those applications where hydrogen might be considered to have a technological or commercial edge over alternatives and in consequence where it might first emerge. When defining future demand it has been assumed that for certain applications such as transportation, hydrogen and fuel cells predominate but allowance is made for the use of biofuels and pure or hybrid electric vehicles thus "reducing" demand for hydrogen. However, these other technologies are not explored in any depth since this was not feasible within the timescales of the research.

### 2.5.5 The Hydrogen Energy Economy

As was briefly discussed in Section 1.3 and will be expanded upon in Section 2.6 of this Thesis, a significant body of literature exists to describe what is understood by the "Hydrogen Economy". It is probable that each country or region would interpret the concept of the hydrogen economy slightly differently but in essence it could be understood as the introduction of hydrogen as a major fuel vector satisfying a significant proportion of end-user demand for energy. Clearly any country can be either a developer or a user of hydrogen technologies (or both, as in the case of

Canada, for example) and they could offer technology or services on a domestic or international basis. Opportunities exist within the UK to develop businesses in any of market area related to hydrogen and fuel cells, whether that be products, services or technologies, and accordingly a hydrogen energy economy could refer to one where one or more of these products, services or technologies are developed in the UK. Indeed, it would be possible in theory to develop competences in any given area without there being a wholesale shift towards the implementation of a hydrogen infrastructure in the UK. However, for all practical purposes this description is rather too simplistic for any analysis of the impact on the UK economy of a major shift, domestically or globally, towards the application of hydrogen in the energy value chain. However, by making reference to this chart it is possible to qualitatively discuss where the UK might seek to be positioned and, accordingly, what the impact might be on GDP. BERR in its "Strategic Framework for Hydrogen Energy in the UK" [12] has already identified a number of areas where it believes the UK to have particular strengths in the hydrogen field as shown in Table 2.10.

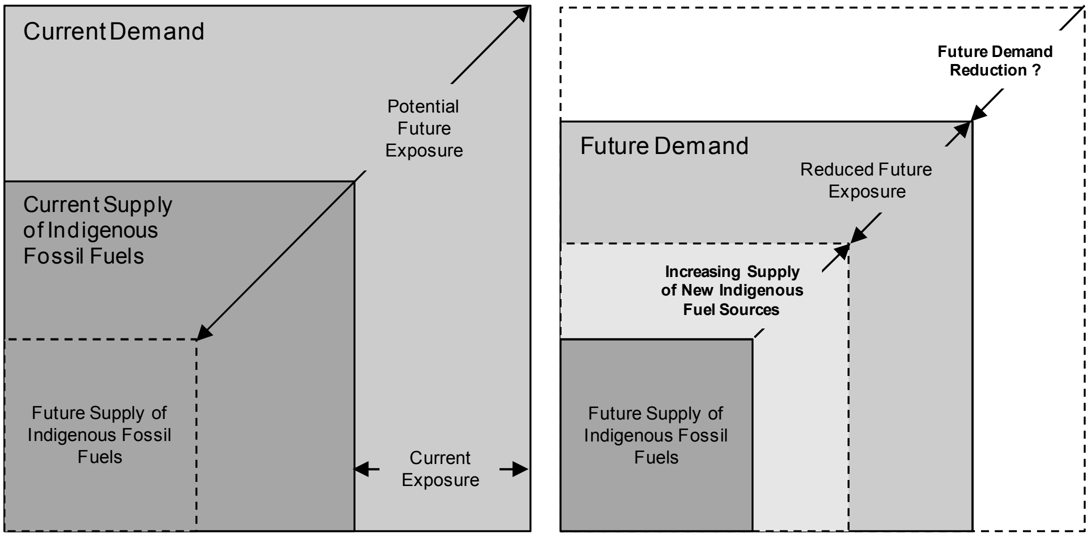
| **Supply Chain Activities** | **Hydrogen Energy Chain Position** | | | | |
|---|---|---|---|---|---|
| | **Production** | **Storage** | **Distribution** | **Conversion** | **Cross-Chain** |
| **R&D** | XX | XX | XX | XX | X |
| **Component Manufacture** | XX | X | XX | X | X |
| **System Manufacture** | XX | X | X | X | X |
| **End-user** | XX | XX | XX | X | XX |
| **Installation, operation** | XX | XX | XX | X | X |
| **Enabling Activities** | X | X | X | X | X |

*XX = strong activity in UK context* *X = limited activity in UK context*

**Table 2.10 Perceived UK Strengths in Hydrogen and Fuel Cell Technologies**

### 2.5.6 Supply Security and Energy Hedge

As has been previously discussed, the UK economy currently enjoys something of a natural hedge against movements in the price of fossil fuels, due to it having both significant production and consumption. However, as UKCS production declines so this hedge becomes less perfect as Figure 2.12 demonstrates.



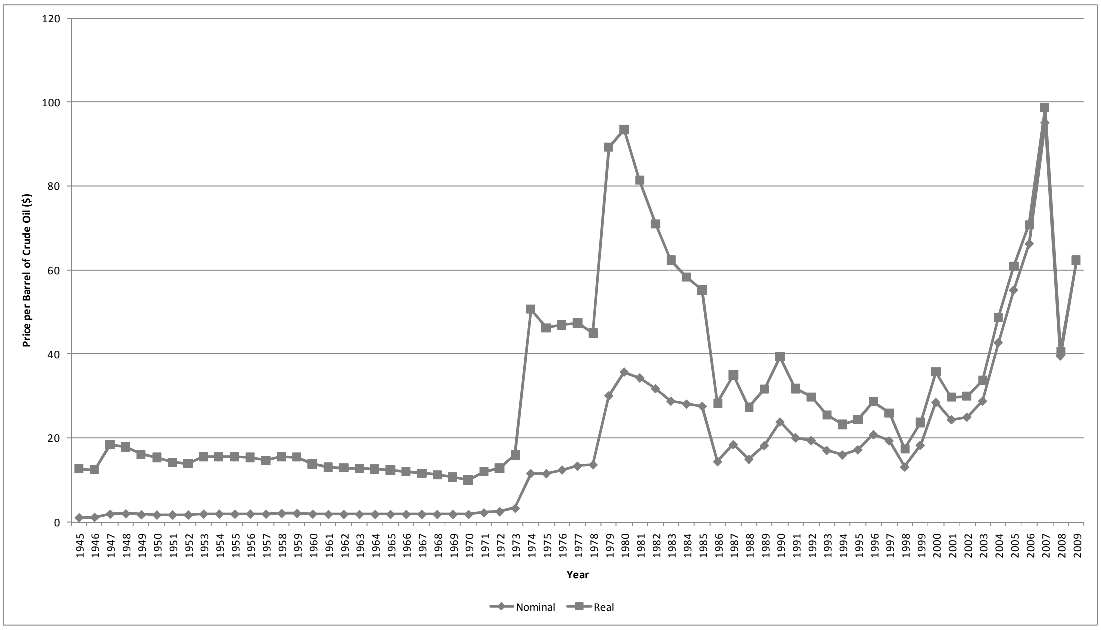

*Note: Size of squares proportional to quantities of supply and demand (not to scale)*

**Figure 2.12 Illustration of Hydrogen's Potential Role in Reducing Future Security of Supply Issues**

By taking steps to reduce demand and increase the usage of alternative indigenously-produced energy, the quality of the hedge could be improved again, potentially even beyond the current situation. This new situation is illustrated in the right hand side of Figure 2.13 with the future un-hedged portion of demand being squeezed by reducing demand and increasing indigenous supply. There is clearly value inherent in reducing dependency on fossil fuels and the use of a combination of both energy saving measures and new technology developments is likely that this will be addressed through a combination of supply and demand-side measures. Hydrogen could have a useful role to play, particularly in areas such as transportation where all of the current alternatives to oil have issues associated with them.

### 2.5.7 Fuel Price Volatility Protection

As briefly discussed in Section 2.2.1, it has been advanced by a number of observers [67] that changes in fossil fuel (and particularly oil) prices have an adverse impact on gross domestic product. The IEA, for example, has estimated that a $10 increase in the price of oil could reduce global GDP by 0.5% [68] while Hamilton showed that oil price rises preceded seven out of eight recessions between 1945 and 1980.




*Source: Commodity Research Bureau 2010, Price for the period 1945 – 1985 is that for Arabian Light posted at Ras Tanura, while for the period 1985 – 2009 Brent Spot [69]*

**Figure 2.13 Real and Nominal Crude Oil Price 1945 to 2009**

As Awerbuch [34] observes in relation to the oil price graph in Figure 2.13:

"Oil price movements from 1948 to 1980 generally took the form of [nominal] price increases. This pattern abruptly changed with the 1986 price collapse, which initiated a series of large positive and negative price swings reflecting a substantial rise in oil price volatility, defined as the standard deviation of periodic changes."

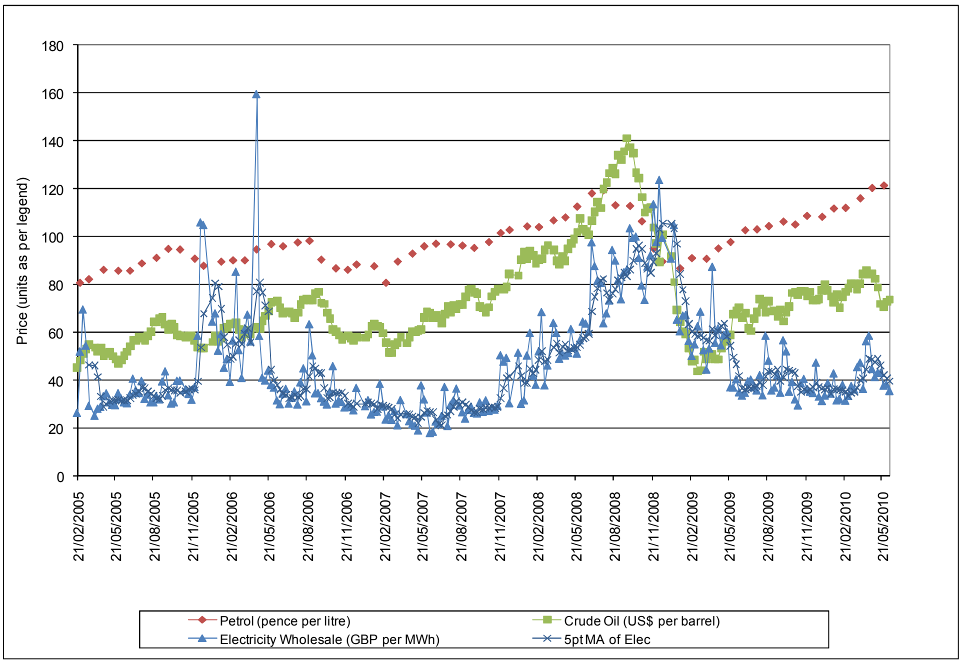
For much of the post war period, therefore, oil price changes took the form of price increases and empirical models of the oil-GDP effect focused on the correlation with the absolute price. However, the oil price collapse in 1986 signalled the advent of a period of significantly increased price volatility and observers started to take note of the influence of price shocks on GDP. Table 2.11 clearly demonstrates the considerably higher price volatility (as measured by the standard deviation) in the later periods compared with the earlier ones as well as generally higher real and nominal prices. To reinforce this point, the mean and standard deviation of the nominal and real crude oil price for six periods between 1945 and 2009 are presented in Table 2.11.

| | Nominal oil Price ($ per barrel) | | | | Real Oil Price ($ per barrel) | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Max | Min | Mean | SD | Max | Min |
| 1945 – 1959 | 1.8 | 0.3 | 2.1 | 1.1 | 15.2 | 1.6 | 18.4 | 12.4 |
| 1960 – 1970 | 1.8 | 0.0 | 1.9 | 1.8 | 12.2 | 0.9 | 13.9 | 10.6 |
| 1971 – 1980 | 10.2 | 8.6 | 30.0 | 1.8 | 37.6 | 25.1 | 89.2 | 10.0 |
| 1981 – 1990 | 25.2 | 8.0 | 35.7 | 14.4 | 54.4 | 23.4 | 93.4 | 27.3 |
| 1990 – 1999 | 18.5 | 2.9 | 23.8 | 13.1 | 26.9 | 5.9 | 39.3 | 17.4 |
| 2000 – 2009 | 46.7 | 22.9 | 94.9 | 24.4 | 51.1 | 22.2 | 98.7 | 29.7 |

*Source: Based on data from Commodity Research Bureau 2010*

**Table 2.11 Means and Standard Deviations of Nominal and Real Oil Prices 1945 – 2009**

A number of authors have observed that volatility creates uncertainty and stifles investment as a result of the inflexibility of capital and labour, thus depressing GDP. For example, research by Lee et al [70] was able to overlay a price shock factor over the oil-price-rise-GDP model developed by Mork [71] with the result being a much more closely correlated relationship. Despite the strong evidence to support the thesis for the oil-GDP effect there are nevertheless detractors. Observers often point to the fact that companies have instruments available to them to hedge against oil price changes but while many companies purchasing or supplying fossil fuels have the ability to hedge their exposure against price volatility there is a cost associated with achieving this and owing to supply and demand uncertainties hedges rarely provide 100% coverage [72]. Indeed unless companies are particularly risk adverse they would typically not wish to hedge their entire position, leaving some opportunity to realise upside benefit where oil prices move in their favour. What is more, despite the fact that a large number of market participants have the ability to hedge their position, there is also a large number of consumers which are not able to either because the facility does not exist or because it would be too costly to do so. Where domestic energy consumers are concerned there is a certain amount of statutory protection which exists to insulate customers from high price volatility but this regulation has been gradually stripped away from all but the most vulnerable. As global demand for fossil fuels continues to increase, readily available supplies begin to decline and supply disruptions potentially escalate, price volatility might be expected to increase rather than decrease. Indeed evidence from the more recent period suggests that the overall trend has been towards higher volatility in energy prices in general and oil and gas prices in particular [73].




*Source: [74] (petrol price); [75] (electricity spot price); [20] (crude oil price)*

**Figure 2.14 Nominal Electricity and Petrol Prices 2005 – 2010**

Figure 2.14 amply demonstrates this point and suggests potential interdependence of energy pricing. As already mentioned, inherent market volatility has an effect on the investment decisions of companies in the sector which must rely on expectations regarding input costs and output prices in investment planning. At a qualitative level, greater price volatility might lead investors to be more reluctant to invest since the uncertainty makes the value of the investment less certain. Companies might employ a number of different methods for coping with that uncertainty but typically this would influence the discount rate used in the analyses. Thus the greater the volatility the higher the discount rate employed which would tend to have the effect of reducing the number of projects *ceteris paribus* found to be NPV positive. The idea is advanced here that renewable hydrogen has the potential to demonstrate lower price volatility and by extension attract a lower discount rate thus improving returns for hydrogen projects relative to fossil fuel based alternatives. A similar argument has been made by Awerbuch and Sauter [34] that investment in renewable electricity generation (RE) can, through the avoided oil GDP losses and consumer savings from lower gas prices, create wealth for further investment in RE. The argument in relation to renewable hydrogen is even more direct since it does not rely on the substitution of natural gas in the electricity generation mix implied in Awerbuch's model. This is illustrated in Figure 2.15 and illustrates how reducing the demand for oil should have the effect of reducing oil prices, and potentially volatility, and thus improve overall GDP through the avoided oil-GDP losses.

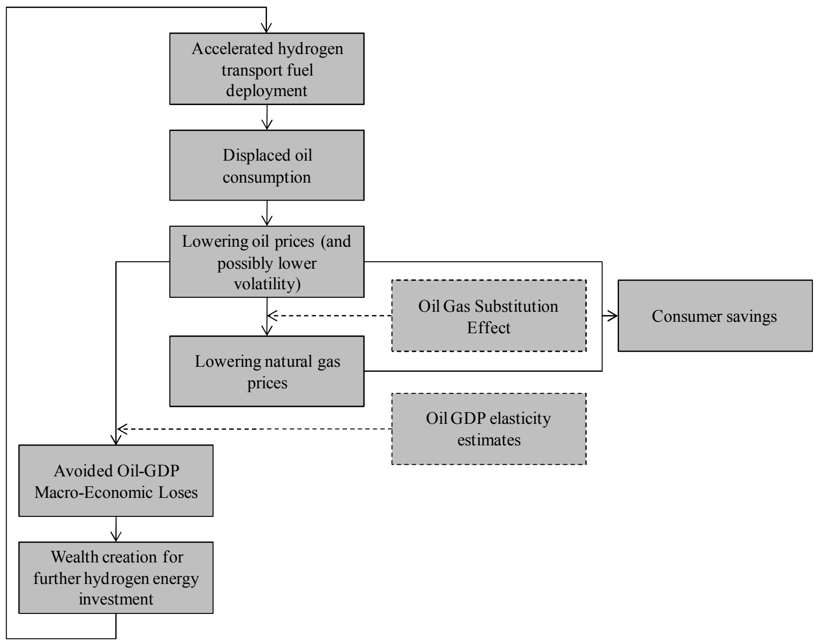



**Figure 2.15 Schematic Representation of the Value Creation Achievable through Oil Substitution in Transport Fuel**

Thus there is potentially a dual benefit from investing in hydrogen infrastructure; the first being the reduction in GDP losses and the second being the application of a lower discount rate to reflect the lower inherent volatility.

## 2.6 Literature Review

### 2.6.1 Introduction

The author's research contributes directly to the body of literature that is described here as hydrogen futures. McDowell and Eames [8] have provided an excellent review of the extant literature in this domain which is discussed in more detail in Section 2.6.2 and has provided a useful framework for the author. Within their typology this Thesis falls into the Descriptive Model category and within that category would be placed under the heading of a Forecast, described as being:

"…characterised by the use of quantitative methods to predict futures based on current trends, or based on surveys of expert opinion."

As will be shown, the author's model demonstrates novelty compared with the current models being employed in its approach to forecasting, which is predicated on an analysis of the relative value contribution of different systems to companies in the sector. This is in contrast to existing models where adoption rates for hydrogen energy systems are, as McDowell and Eames observe, largely a function of their relative costs compared with alternative technologies.

In light of the relatively early stage of development in the hydrogen energy sector, the author considered it pertinent to compare research in the hydrogen energy field with the broader energy forecasting literature, making particular reference to the electricity supply industry (ESI). The logic for doing this is threefold.

- Firstly a considerable body of literature exists describing the behaviour of companies in the ESI which dates from the privatisation of the ESI onwards and hence may provide useful data for validating the author's approach.
- Secondly, there are obvious parallels between hydrogen and electricity where both are energy carriers rather than energy sources in their own right.
- Finally, the electricity supply industry (ESI) has particular relevance to the current analysis, given the linkage to the ultimate goal of renewable (or "green") hydrogen.

While not exactly analogous to the development of a completely new market (such as hydrogen energy would represent), it is thought that the investment decisions relating to new generation capacity in the ESI (sometimes referred to as Generation Expansion Planning, GEP) can offer useful indicators of company behaviour when considering the development of hydrogen energy infrastructure. This wider review provided evidence of the use of alternative models for forecasting energy infrastructure investment and the work of Botterud [1] and of Gross [76], for example, provided valuable direction to the author's research while confirming the novelty of the author's approach. Two further important bodies of literature were reviewed pertaining to the building blocks of the model, namely the investment literature and simulation literature. The first literature encompasses the factors which govern, on the one hand, the drivers of investment in physical assets and, on the other hand, the related subject of what drives fund-raising to support investment in physical assets. The second literature describes the methodologies applied to simulation. The review of these bodies of literature was carried out principally to provide context to the detailed aspects of the model and to confirm the current state of thinking in these areas and has helped to support and inform the approaches taken by the author in developing the current model. The positioning of this Thesis in relation to these bodies of literature is provided in Figure 2.16.

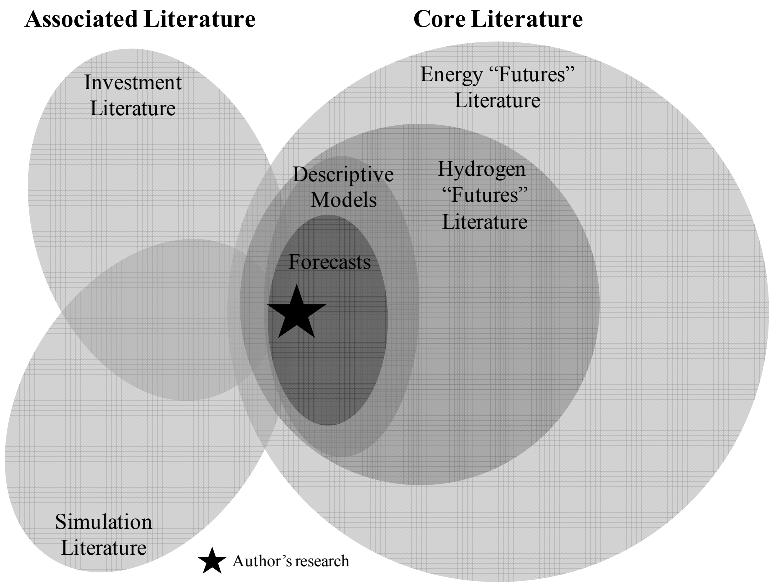



**Figure 2.16 Related Areas of Literature and Positioning of Author's Thesis Work**

In the following sections the principal themes and publications in each of these bodies of literature are identified and the current research is discussed in its context, highlighting the aspects of differentiation in the author's work.

### 2.6.2 Hydrogen Energy Futures Literature

As McDowell and Eames [8] have identified, the literature on hydrogen futures is extensive and wide ranging with a variety of approaches being taken to describe and explain potential market development, some quantitative and others qualitative. In light of this diversity, McDowell and Eames propose a typology for critical analysis of work carried out to date which the author has found useful in positioning this Thesis and other work in the hydrogen energy domain. This framework is summarised in the following paragraphs.

#### 2.6.2.1 Descriptive models

As the name suggests, such models aim to describe future scenarios based on the extrapolation of current trends or the analysis of key industry drivers. McDowell and Eames point to three different types of descriptive model.

- *Forecasts* – These studies are "characterised by the use of quantitative methods to predict futures based on current trends, or based on surveys of expert opinion." [77] Inputs tend to be factors such as fuel cost and oil price projections, characteristics of competing technologies and demand projections. Rates of adoption are "largely a function of their relative costs compared with alternative technologies." McDowall and Eames note that this approach is often criticised for failing to recognise the paradigm shift implicit in such dramatic technological change. The author believes the work presented in this Thesis is best identified in this category of model;

- *Exploratory Scenarios* – Such scenarios seek to explore underlying drivers of change in order to explore a number of alternative possible futures [78]. While drawing upon tacit knowledge and expertise they nevertheless explore less certain futures, perhaps further ahead in time, and include the effects of trend-breaking developments. Since these studies tend to be more top-down in approach [79] they may suffer from a lack of granularity with respect to the outcomes; and
- *Technical Scenarios* – According to Hart et al [80], the purpose of these technical scenarios "…is not to predict the uptake of alternative fuels…, but to assess the implications of such a large-scale move, should it be attempted." These studies endeavour to synthesise and assess the implications of a variety of possible technological developments against a range of criteria including carbon emissions, costs and technical feasibility [81]. McDowell and Eames remark that, having a rather technological focus, these studies may fail to take account of the social or cultural dimensions of change. Given the emphasis of the Author's model on developing detailed representations of constituent hydrogen plant, the current research is also comparable with these studies in some respects.

#### 2.6.2.2 Normative models

Unlike descriptive models, normative models set out a vision for the future and investigate the steps that would need to occur in order for such a vision to be achieved. Once again, three categories are proposed.

- *Visions* – Visions typically describe a positive, possibly utopian, picture of a future hydrogen energy economy aiming to show that it is both plausible and desirable. Studies are not typically temporal in nature but instead focus on the outcome and tend to emphasise large-scale shifts in technology or social values as catalysts of change [82]. Such research is much less quantitative in nature but instead qualitatively describes a world where electricity and hydrogen co-exist and provide the basis for society's energy needs. Such studies draw criticism from certain quarters for the general lack of detail with regard to the steps required to attain the goal;

- *Backcasts & Pathways* – Rather like the Visions, such studies begin with the premise that a hydrogen energy future is desirable and achievable and then investigate the steps that would need to occur in order for such an outcome to be achieved [83]. They are frequently under-pinned by relatively simplistic models of technological change; and
- *Roadmaps* – Rather like backcasts in approach they differ in terms of their view of future development. The approach taken is to identify the barriers to emergence and growth of a future hydrogen energy economy and identify how to overcome them through the setting of targets [84]. In doing so, such research offers advocacy for the vision provided and frequently tries to draw together a group of relevant stakeholders to develop and share the vision. Frequently seen as offering too "rosy" a view of the future, such studies nevertheless offer clear targets to work towards.

McDowell and Eames draw a number of specific conclusions about the findings from the reviewed research, which while of considerable interest to the wider subject, are of less interest to this current comparison. Of greater interest are the conclusions they draw regarding the shortcomings of the research covered by their literature review, which can be summarised as follows:

- Lack of underlying theoretical model for development;
- Lack of transparency and participation;
- Lack of distinctness and clarity in roadmaps;
- Recycling of predictions, forecasts and targets in the literature;
- Literature tends to provide a too top-down view;
- Lack of systematic assessment of broader sustainability impacts;
- Treatment of hydrogen as a standalone technology not one embedded in broader energy systems.

When describing the author's work, specific reference is made to how it addresses certain of these concerns.

### 2.6.3 Energy Forecasting Literature

While the author's Thesis draws on thoughts and concepts from a wide body of hydrogen literature, it is primarily concerned with developing what McDowell and Eames describe as a method of forecasting. In consequence, the author's own review was most interested in understanding what approaches were being taken to quantitative forecasting throughout the energy sector and in confirming the novel aspects of the author's work. An extensive review of both the hydrogen energy and general energy forecasting literature has been undertaken which clearly identifies that the investment-led approach developed in the current Thesis has not been applied to the hydrogen energy sector and that it represents a novel way to approach market forecasting.

This meticulous review confirmed what McDowell and Eames had themselves already identified that cost optimisation approaches predominate in the development of forecasts. The basic concept of least cost optimisation is simple; an energy system will be introduced into the overall energy mix if and when the system cost is competitive with the alternatives available at the time. One such model, the so called Market Allocation (MARKAL) model [10], has been used extensively by national and supra-national organisations, including the UK Department of Business Enterprise and Regulatory Reform (BERR formerly the Dti) [12] [80] [85], the US Department of Energy [13] and the European Union [14], to develop forecasts for the introduction of hydrogen into the wider energy mix. The MARKAL model is technology-rich and takes a bottom up approach, building a picture of energy systems from a series of individual component modules representing existing and future plant and applications. It has been enriched through the collection of considerable empirical data relating to the performance, efficiencies and total cost of operation of these plant and applications over time. Needless to say, the component modules are necessarily more speculative when representing the likely cost evolution of newer energy sources and vectors but these new energy models are based upon knowledge of typical learning characteristics, expected economies of scale, and so on and may be considered to provide a realistic picture. The reliability of the model is enhanced by performing multiple runs under different scenarios so that the resilience of the model results can be effectively tested. At its heart, the model makes trade-offs between different technologies based on system cost and though it does allow the introduction of a variety of constraints such as limitations on the level of aggregate carbon emissions or on the relative proportion of different energy sources in the overall mix, it does not solve for these variables. The application of certain of these constraints has been embodied in the Macro-MARKAL model being developed by PSI and UKSHEC [86] and which is being used in their next generation of forecasting with regards to hydrogen and other low-carbon technologies. Tseng et al [13] provide a useful and succinct description of the MARKAL approach as follows:

"MARKAL is a partial equilibrium model of a group of energy systems. It is a dynamic linear programming model that is run in 5-year intervals...The objective function includes the capital costs of end-use (demand) technologies, the capital costs of energy-conversion technologies (e.g. power plants, petroleum refineries), fuel and resource costs, infrastructure costs (such as pipelines), and operating and maintenance costs. The model tracks new investments and capital stocks between periods. It searches for a least-cost solution dynamically over the forecast period...to meet user-specified energy service demands, such as heating, cooling, lighting, and vehicle kilometres travelled. Because the model integrates both demand and supply technologies into a single energy market, the solution represents a partial equilibrium in which the energy system's cost is minimized over the selected period."

Tseng's representation of the MARKAL model implementation for the US is shown in Figure 2.17.

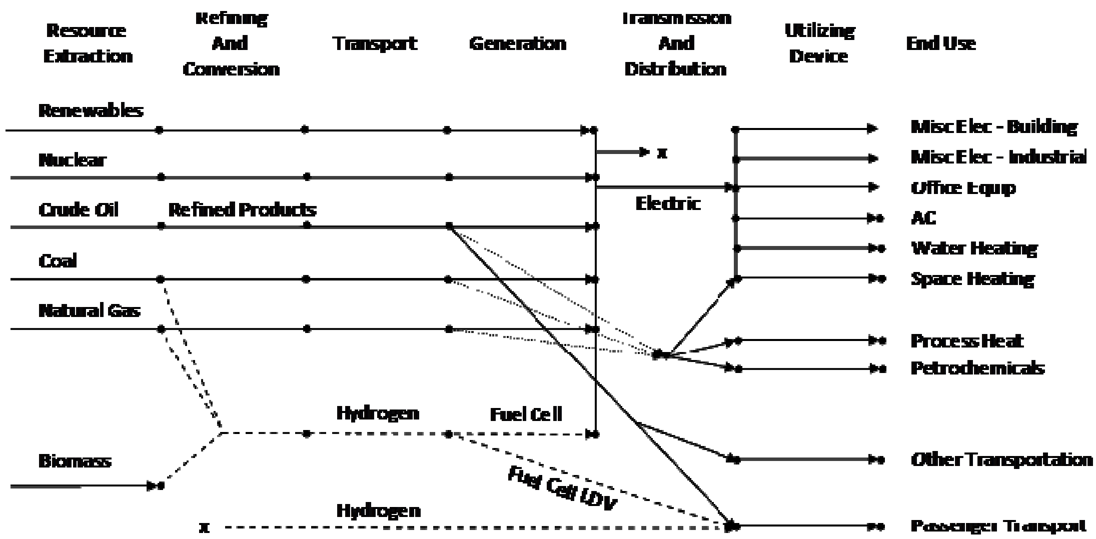



**Figure 2.17 Schematic Representation within MARKAL of the Introduction of Hydrogen into the Overall Energy System**

MARKAL was developed primarily as a planning tool to enable governments to ensure that their energy needs would be met in the most cost-effective way and as Schwarz and Hoag discuss in their paper on the interpretation of energy model results [87]:

"Abilock & Fishbone's [88] [two of the model's creators] description of the MARKAL program emphasizes that MARKAL is *not* a forecasting or prediction model and that it is primarily designed for comparisons of the competitiveness of new energy technologies."

However, as Schwarz and Hoag go on to say, this presents the user of the model with a dilemma since:

"...if future-oriented models are not meant to be used for forecasting purposes, how should they be used...and...can or should any kind of validation be required?"

The second aspect of this statement is discussed in more detail in Section 3.7 but the first part points to a subtle shift which seems to have occurred in the way that MARKAL is being used. In the hands of the central planner, the model might be used to explore the timeframe in which it will be feasible to start introducing one technology or another. However, in a competitive market the temptation to treat the output as a forecast is compelling; once again referring to Schwarz and Hoag, the point is made that:

“...despite the fact that some future-oriented models have been explicitly presented as non-forecasting models, there seems to be a tendency to interpret model outcomes as "forecasts," i.e., relatively unconditional propositions about what will actually happen in the future.”

Thus, national and supra-national organisations frequently use MARKAL “forecasts” to underpin the development of policy [89], providing both a reference point for the structuring of policy and a means to test the effect of different policy measures. While the author would take issue with the suitability of systems-based models to inform policy, nevertheless, as Tseng observes, the commonly held view is that:

“[MARKAL] is especially useful in examining polices that change the technology menu, such as introducing hydrogen-supply and fuel-cell technologies to the transportation sector. Energy-efficiency regulations, caps on energy-related emissions, caps or floors on specific types of energy use are also examples of policies that can be modelled easily. Additionally, policies that explicitly or implicitly tax or subsidize specific technologies or energy forms can be modelled.”

Alongside and closely related to the least-cost MARKAL model are a set of tools focused on investment planning, including models such as the Long-Range Energy Alternatives Planning (LEAP) [90] or Wien Automatic System Planning Package (WASP) [11]. These planning tools are also built around cost-based analyses and although, according to the associated literature [90], LEAP does not have optimisation functionality, it allows users to explore possible future scenarios across a wide range of energy sectors. Luhanga et al [91], for example, have used LEAP to consider possible scenarios surrounding biomass energy in Tanzania. WASP, on the other hand, provides a full range of functionality including the least-cost optimisation facility but is only applicable to the electricity supply industry and, specifically to generation investment planning. In parallel with supply-side models such as WASP, specific tools designed to model the demand side such as the Model for Analysis of Energy Demand (MAED) [11], have also been developed, in this instance by the International Atomic Energy Agency (IAEA). Interestingly, in Kitous' World Energy Model, developed by him in collaboration with Enerdata, both the WASP and MAED models are used to provide input data to the core optimisation engine [92].

Philosophically speaking, the use of least cost methodologies in planning tools, particularly when applied to monopoly markets, would seem to have a more satisfactory logic than would their use in forecasting. In light of the non-profit-making nature of the monopolistic, nationalised energy providers, least cost would certainly represent a compelling objective for such organisations. It is also relatively easy to see that there might be a desire at government level to drive towards a lowest cost set of energy systems. Many OECD countries are currently net energy importers, and their governments tend to view energy as primarily a factor of production and de-emphasise its role in generating wealth. Thus, it is argued, the lower the cost of energy the higher is GDP. However, two points are worth noting in relation to this statement. The first has already been alluded to in Section 2.2.2, and concerns the potential for the energy industry to be a net contributor to GDP. In this instance higher energy prices have the potential to increase GDP for a given nation. The second is that the GDP cost of energy should reflect the total system cost taking into account the effects of price volatility as discussed in Section 2.5.7. Taking these issues into account, it is apparent that even in the case of planning for a monopolistic energy regime there is a need to treat the least-cost methodology with caution.

Elsewhere, in developing their own MESSAGE-based model [93] to assess the potential for hydrogen energy in the Spanish market, Brey et al. [94] continue the least-cost theme, arguing that:

‘‘[it is obvious that], regardless of any other criterion, it is preferable to carry out the first phase of the transition process [to the hydrogen energy economy] at the lowest economic cost.’’

As can be seen, the implicit assumption is that companies looking to exploit hydrogen would be primarily led by the cost differentials not the revenue opportunities, an issue that will be discussed further in Section 2.6.5.

Considering the broader energy forecasting literature, Jebaraj and Iniyan [95] provide an interesting and wide ranging review of the different approaches taken to energy forecasting over time and in different geographical regions and offer insights into current thinking. Jebaraj and Iniyan identify a significant body of literature that falls into the category they refer to as “optimisation models” and confirms the proclivity for cost-optimisation approaches. They cite the use of MARKAL alongside other models such as MODEST [96], EFOM [97] and MESSAGE [93], which, in his paper describing a model of local area electricity and district heating [98], Henning links explicitly stating that:

“Energy forms and processes from primary energy to useful energy may be described for a country using the MARKAL (MARket ALlocation), EFOM (Energy Flow Optimisation Model) or MESSAGE (Model for Energy Supply Systems Alternatives and their General Environmental impact) model”

What is apparent from this paper is that there appears to be a high degree of inter-changeability between these models although differences at the detailed level do exist such as the time periods used for demand scenarios. In Henning’s paper MODEST is positioned as an alternative suitable for a specific application but, once again it does not represent a fundamental departure from the underlying principles used in the other models.

In contrast to the cost optimisation models both Christidis [99] and Criqui and Mima [100] have applied the Prospective Outlook on Long-term Energy Systems (POLES)

[101] model to various energy problems. POLES takes a partial equilibrium econometric model approach to solve for energy supply and demand across 57 global countries or regions and differs fundamentally from the cost-optimisation model in that it constructs supply and demand scenarios across regions and outputs resulting expectations on price. Sometimes referred to as an intermediate model, it combines elements of both the top-down macro-economic view and the bottom-up systems view as Kitous discusses [92]. Despite the obvious differences in approach there are nevertheless similarities with many of the cost optimisation models in terms of philosophy. Principal among these similarities is the focus on systems and regions rather than on the behaviour of companies. In their oft-cited paper [102], Criqui and Mima use POLES to construct worldwide Marginal Abatement Cost (MAC) Curves in each of the POLES regions, reinforcing the relationship with the cost minimisation approaches. In other attempts to move away from the cost approach, Orion Innovations in their report for the Scottish Hydrogen and Fuel Cells Association use a model of supply and demand on the basis of half hourly time slots to estimate how much "spare" electrical capacity was available to produce hydrogen under various scenarios [103].

If the cost-optimisation approach has predominated the forecasting literature to date, the author's review highlights a more recent body of research that has begun to question the extent of the validity of the concept. For example, Gross et al in their white paper for the Imperial College Centre for Energy Policy and Technology (ICEPT) [76] make the observation in respect of the ESI, that:

"Policy decisions on power generation are often informed by estimates of cost per unit of output [and] [t]hese are used to provide a 'ballpark' guide to the levels of support needed (if any) to encourage uptake of different technologies. [However,] [w]hile cost estimates can help indicate whether support is warranted, cost alone is not always a good guide to *how* to intervene. This is because the private companies making the investments will take into account a range of factors that are not captured well, or at all, in levelised cost data."

There is an implicit recognition in this statement that a drive to cost minimisation may not be the sole, or even the primary, objective of companies in a competitive, decentralised and unregulated market. Botterud [1] makes this point more explicitly stating that:

"…the centralized least-cost planning approach does not reflect how investment decisions are made…where several…companies are competing with each other…"

In their review of power generation planning before and after the onset of privatisation or competition, Kagiannas et al [104] make the observation that:

"The traditional aim of an electric power utility has focused on providing an adequate supply of electric energy at minimum cost...However, the way that generation expansion planning has been approached and solved has been totally redirected through the introduction of competition and deregulation of electricity markets. The problem of power [generation expansion planning] has been reformulated from being cost-minimisation to profit-maximisation. The privatised approach evaluates a resource alternative's benefits according to its own revenue stream."

Recent policy output from the UK government such as the Low Carbon Transition Plan [39], specifically refers to the use of MARKAL forecasts as the basis for the model. However, interestingly, in the Renewables Strategy [89], the comment is made that:

"The precise breakdown of the 2020 renewable energy target between technologies will depend on how investors [i.e. companies] respond to the incentives we put in place."

The implication would seem to be that the MARKAL model provides a forecast of the point at which the market would arrive in the absence of particular policy measures without specific reference to the behaviour of companies. By contrast the policy measures by definition are (indeed, must be, despite Tseng's assertion referred to previously) assessed with reference to the behaviour of the competitors in the market. This dichotomy is one of the things that the author's investment led model seeks to address by integrating the investment behaviour of the company into the initial forecast.

Returning to the hydrogen forecasting literature, Ball et al in their paper on the possible development of hydrogen energy infrastructure in Germany [105], pick up on the theme of the limitations of the single target function implied by the cost optimisation models. In privatised energy markets where investment is undertaken by individual companies they point out that:

"One weakness of the developed model [MOREHyS] approach is the central, one-dimensional optimisation which assumes the same target function for all participants. The model identifies possible economic and environmental benefits of a hydrogen infrastructure build-up by determining the global optimum for the whole system instead of the optimum for each company."

While not made explicit, it could be assumed that optimal objective of each company could be the maximisation of shareholder value.

It is evident that the issue of what drives companies to invest has preoccupied policy-makers in the UK since the days of the initial privatisation of the ESI, and a significant body of literature exists looking at the investment decisions of firms in the ESI, whether investment in generation (GEP) or distribution capacity. The roots of these analyses can be traced back to the preparation of the large scale privatisations of the European ESI which began in the UK in 1989. The consultation at that time required a detailed discussion of the drivers of investment [106] and provides within the basic price setting regime, an allowance for annual investment. This was represented by the classic RPI – X + Y formula where RPI is the retail price index (inflation), X an efficiency improvement factor and Y an allowance for capital investment. While the regulatory regime surrounding the ESI has changed out of all recognition since that time, the question of what drives investment in the ESI continues to attract considerable interest as the industry has suffered a series of investment boom and bust cycles. This interest has increased since 2000 as it has become apparent that there will be a potentially significant shortfall in generation capacity over the next decade and that large sections of the grid infrastructure will need replacing or strengthening not least in response to the considerable planned build-out of renewables capacity.

In light of this, GEP benefited from the application of a wide range of modelling techniques. While up to now, this Thesis has been concerned primarily with discussing the evaluation methods being considered by forecasters, when looking more closely at GEP another aspect of modelling comes to the fore, namely the different simulation methodologies being employed. Techniques in simulation can be classified in a number of different ways but one useful approach [107] is to classify them along paired attributes such as:

*Stochastic or deterministic (and as a special case of deterministic, chaotic)*

Statistical models explicitly recognise that input variables will demonstrate a range of possible values which can be described by, for example, a normal distribution. Statistical techniques range from the very simple, such as the probability weighting the sensitivity analyses described later in Section 3.5.3.1, to methodologies such as Monte Carlo simulation (discussed in Section 3.5.3.2) and adaptations such as Markov Chain Monte Carlo [108]. This allows a range of possible outcomes to be analysed in a more complete way. By contrast, deterministic models describe systems in pre-determined form delivering a single output (or set of outputs) for a given set of inputs. These models are typically subjected to sensitivity analysis or scenario modelling in order to test the boundaries and limitations of the model.

*Steady-state or dynamic;*

Steady-state models are those in which the behaviour does not vary over time and can be described using simple algebraic equations. Dynamic models on the other hand seek to mimic the changing behaviour of systems and are typically modelled using differential equations.

*Continuous or discrete*

This describes the approach taken to the series data which may be either continuous or discrete.

While the typology described above is considered a useful one, for the purposes of this Thesis the principal methods being employed in GEP are shown in the matrix presented in Figure 2.18 which positions research along two axes; the evaluation methodology and the method of simulation.

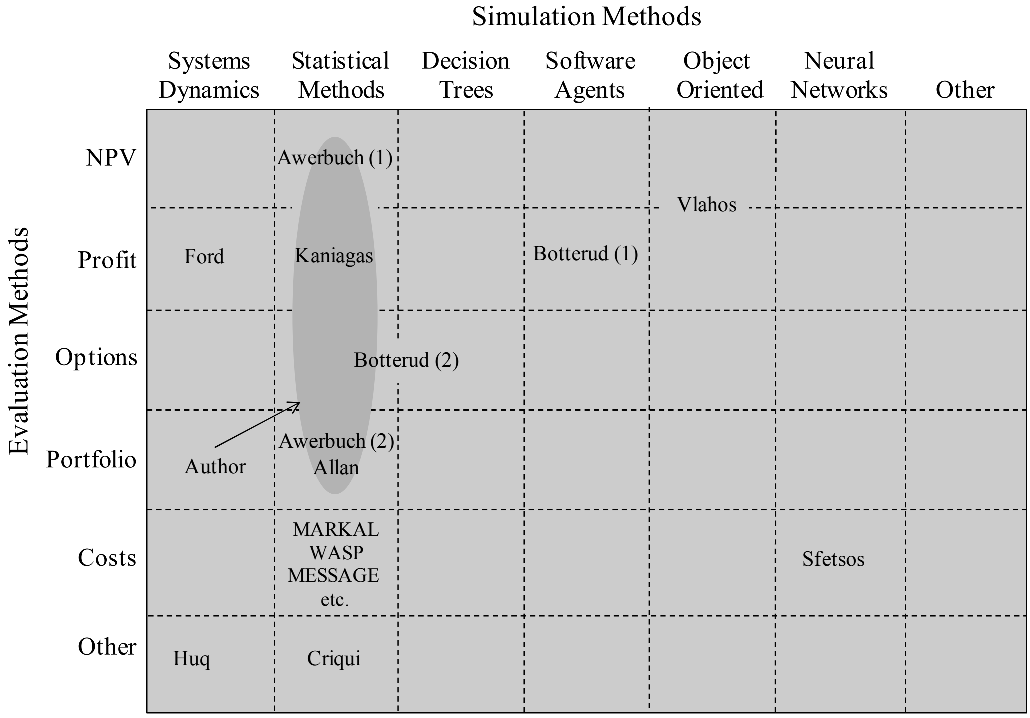



**Figure 2.18 Approaches to Modelling of Investment in Electricity Generation by Evaluation Method and Simulation Technique**

The chart serves to highlight the clustering of modelling around the evaluation metrics of cost, profit and NPV and on statistical methods to assess possible outcomes. The review confirms that, while significant advances have been made in alternative techniques for capital budgeting or investment forecasting, the majority of the literature still relies heavily on methods involving measures of NPV, discounted cash flow (DCF) and profitability. The current thesis also focuses on NPV and profitability as the core comparators between projects on which investment decisions are made and out of which a market eventually develops.

The foregoing analysis points to the need for forecasting models to address the issue of what the constituent companies making up a market consider to be "optimal", otherwise the output of the model will represent an idealised outcome (as would be output from a planning model) rather than a true forecast. It is interesting that Botterud [1], while clearly having reservations about the ability of least-cost optimisation to deliver a realistic forecast in privatised electricity markets, still refers to the least-cost case as being the "optimal" one, stating that:

"...some observers would argue that a well-functioning…market would converge toward the optimal [i.e. least cost] expansion plan...while...others would contend that the independent and decentralized decision-making…leads to suboptimal…plans".

However, in contrast to this viewpoint, the author would argue that the use of the terms optimal and suboptimal is misleading, since what might be considered optimal for a policy maker might not be considered optimal for a company driven by the "profit motive". Although no objective function is suggested in Balls' paper [105], one possible goal could be the maximisation of profit as suggested by Kagiannas [104] or, more generally, shareholder value as is proposed in this Thesis. As will be highlighted in Section 2.6.5, the evidence appears weak that companies in the sector work to converge on the goal of lowest cost but before discussing this evidence there follows a review of extant investment literature (as referred to in Figure 2.16) in order to put this Thesis into context.

### 2.6.4 Investment Literature

One of the complexities associated with developing models built around value maximising algorithms is that there is not a single definition of what is meant by value-maximisation nor what factors drive value. System cost, by contrast, might be thought of as a relatively homogenous concept which perhaps partially explains its currency in forecasting analyses. This section of the literature review aims to provide an overview of the current thinking on drivers of value and the factors underpinning a value-maximisation strategy. Termed here, Investment Literature, this is taken to encompass theories regarding the drivers for, and evaluation of, capital investment and the concomitant drivers of capital-raising which for large investment projects will frequently be linked [109]. Since the current research seeks to shift the emphasis away from systems-based cost-optimising approaches towards a company-centric investment driven approach, it is important to understand key issues such as:

- What drives a company to make capital investment?;
- What impact will those investments will have on the company and its value?, and
- What drives the decisions of investors in those companies?

Since the literature tends to be grouped around specific aspects of this analysis, each of these questions is considered in turn in the review below. However, there are some unifying pieces of work which are discussed in this preliminary section.

Figure 2.19 presents one possible view of a firm and its relationship to investors on the one hand and value-generating investment projects on the other. The term project is used loosely here and is intended to represent any type of new or existing business that the company could choose to develop. These may not therefore be projects in the generally accepted sense of the word but are rather any identifiable businesses from which cash flows and profits may result.

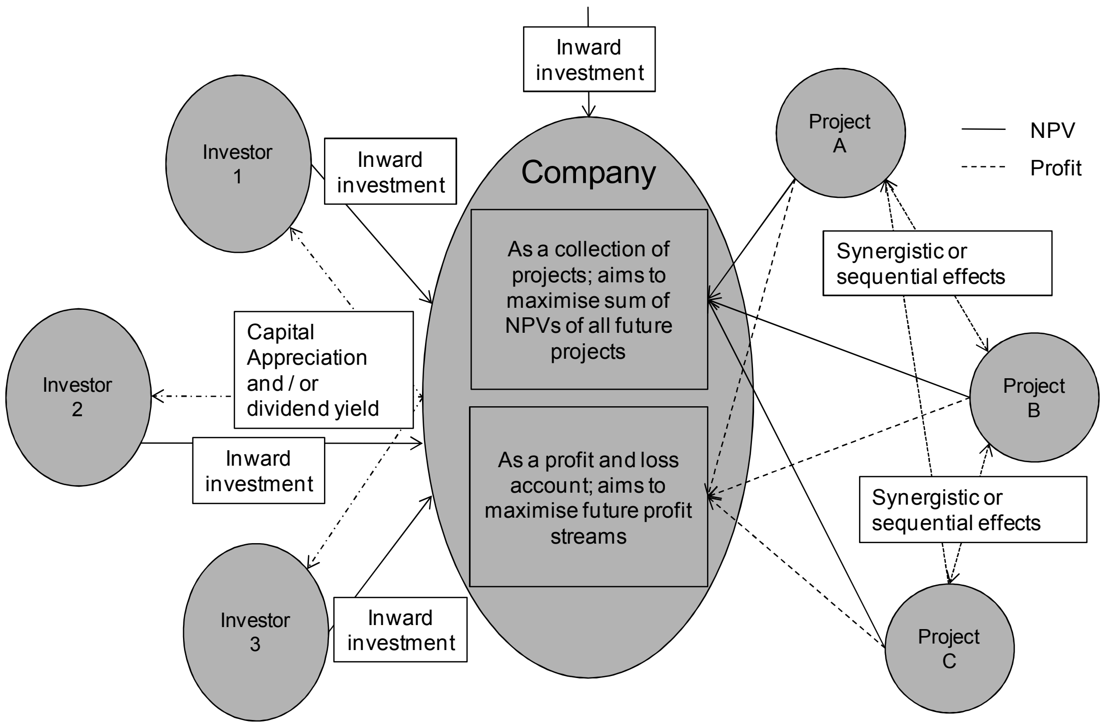



**Figure 2.19 Stylised Representation of a Company: A Stream of Profits or a Collection of Projects**

A company can be considered as an entity able, through its internal labour, skills and competences, means of production and ability to raise capital, to take these projects and realise them on behalf of investors. It has been hypothesised [110] that the principal objective of the firm is to maximise shareholder value above all other considerations. Often referred to as the principal-agent model, investors (i.e., shareholders) pass responsibility through a set of contracts to the company for developing the projects / businesses that may be available to them since they either do not possess the capabilities to develop them themselves, or they recognise that the company might be able to do so more effectively. As Fama puts it:

"The striking insight of Alchian and Demsetz (1972) [111] and Jensen and Meckling (1976) [112] is in viewing the firm as a set of contracts among factors of production. In effect, the firm is viewed as a team whose members act from self-interest but realize that their destinies depend to some extent on the survival of the team…"

Since the investor has provided the capital, it is incumbent on the company to act in the interest of the investor and while other theories exist [113] to explain company behaviour and while no doubt the Principal / Agent theory offers an incomplete picture of reality, it nevertheless has considerable currency and provides a robust starting point for considering the behaviour of firms. One further reason for favouring this approach is that most senior management incentive schemes are based directly or indirectly around the concept of share price appreciation, whether this takes the form of option schemes or bonuses directly linked to absolute share prices [114]. This fact would tend to lend weight to the shareholder maximisation view of the behaviour of firms.

If it is accepted that, above all other considerations, companies will likely seek to maximise shareholder value, it is then necessary to establish what drives shareholder value from an internal perspective. Referring once again to Figure 2.19 it can be seen that firms can be characterised as a stream of profits or as a collection of projects each having its own net present value (NPV). Almost half a century ago, Jorgenson et al [15] proposed that companies are driven to maximise the present value of future after tax receipts (roughly cash profits). Alternatively, the firm could be considered to be seeking to maximise the sum of the NPVs of all the projects it has or will have in its portfolio [115]. The firm then rewards its investors either by paying dividends or through delivering capital appreciation in its share price, with total returns being the sum of the two on a present value basis [115]. Shareholders, it is assumed, seek to maximise the return to their investment although it is worth pointing out that this must be subject to the caveat that it is the maximum return <u>for a given level of risk</u> which is of interest as discussed in more detail in Section 2.6.4.1.

French and Fama in their work [19] on the drivers of returns refer to five factors which have an influence on the return to a given equity and have endeavoured to measure the strength of the relationship empirically (see Equation (1.7)). The effect of price earnings ratio on capital raising is discussed in Section 2.6.4.2 as is the effect on the risk and return profile of a company of the amount of debt it carries. The question of size as measured by the equity market capitalisation of the company is an interesting one and as French and Fama say:

"Whatever the underlying economic causes, our main result is straightforward. Two easily measured variables, size (ME) and book-to-market equity (BE/ME), provide a simple and powerful characterization of the cross-section of average stock returns for the 1963-1990 period."

While not of primary importance to the current study reference is made periodically to the issue of scale and how it might influence the results of the analysis.

#### 2.6.4.1 Capital budgeting literature

If firms invest to maximise shareholder value and if the value of the firm is related to the value of investments it makes, the question of how those investments are valued becomes of critical importance.

The capital budgeting literature might be said to have its roots in the 1960s when the Net Present Value concept was first proposed. The concept is deceptively simple and intuitively robust yet others have observed [116] it is difficult in practice to implement and it is yet more difficult to evidence *ex-post* whether the approach leads to improved decision-making given the measurement difficulties implied. Nevertheless, the approach is the mainstay of much capital budgeting carried out by firms today and has the merit of imposing a certain degree of rigour into the decision-making process, as Bennouna et al assert [117]. Bennouna provides clear evidence of the extensive use of the technique but also highlights aspects of misapplication of the principles and the need for the management of firms to have a better understanding of the processes. Reinforcing this point, in his 1994 paper entitled "Modeling energy technology choices: Which investment analysis tools are appropriate?" [118] Johnson observes:

"Despite the impact of the [alternative] theories described...net present value analysis is still the most commonly used investment analysis method for investment in physical assets."

Prior to the definition of the NPV approach, it was common for investments to be assessed on the basis of payback period which, in reality is broadly similar in its basis to NPV without the important recognition of the time value of money. Many companies today continue to use payback period as a primary method for evaluating projects and it undoubtedly has the advantage of simplicity and robustness.

Two key issues present themselves when considering NPV analysis, namely how to model the uncertainty associated with future cash flows and how to select an appropriate discount rate to which any NPV calculation will be relatively sensitive. A number of methods exist to better simulate future development scenarios and these have been discussed have been discussed in Section 2.6.3, but it is worth mentioning here the extensive body of literature that surrounds the choice of discount rate. Gross et al in their white paper [76] discussing the investment decisions of electricity companies make the point that:

"Policy needs to actively engage with investment risk. This means understanding where risk originates and how it affects investment. Policy analysis needs to model investment scenarios and incorporate revenue risk, rather than focusing largely on costs."

One method for representing risk is the discount rate applied in the discounted cash flow calculations and, pursuing this theme, foremost amongst the models for calculating discount rate is the Capital Asset Pricing Model, which was the result of Sharpe's seminal work [18] to define the expected return to shareholders. This model defines the relationship between the riskiness of a particular investment and the return that the investor should expect to receive, or put another way, the discount rate that should be applied in calculating the NPV of a project of a given riskiness. In fact the model was elaborated with reference to the calculation of the expected returns from a given security (e.g. the stock of a particular company) but, it has been argued, the same principles could be applied to individual projects. However, once again, the model while intuitively straightforward, is relatively difficult to apply in practice and the relationship only holds to a limited extent when applied to empirical data. Once again, Johnson [118] highlights the practical issues associated with the use of the CAPM, stating:

"The CAPM results depend on the assumption of an idealized, frictionless investment environment where everyone has the same information. In particular, all investors agree on the expected returns and covariances of the assets, all assets are freely tradable in any amounts, and there are no transaction costs of any kind. Since the CAPM was developed for securities markets, where these assumptions are arguably approximately valid, their importance is not always emphasized. However, such assumptions are clearly not appropriate for investment in physical assets, where transactions costs are often substantial, investment must occur in discrete and often significant amounts, and sunk costs are common."

However, Awerbuch [34] strongly argues for the application of the CAPM, citing the frequent inappropriate use of Weighted Average Cost of Capital (WACC) methodologies to calculate project NPVs. He states:

"Practitioners think they correctly apply finance theory by estimating specific after-tax…WACC…for different generating technologies. While these are generally correct (with some important caveats) for levelizing or ''annuitizing'' the present value costs, they do not remotely resemble the correct discount rates for the projected capital, fuel and O&M outlays. The discount rates for these costs do not vary by project and are not affected by the way a project is financed. Explicit use has also been made of the CAPM principles when carrying out the sensitivity analysis."

Awerbuch [34] has gone on observe that as the ESI moves from fossil fuels based infrastructure to renewables based infrastructure the risk profile changes with the cost profile. While fuel costs can represent as much as 70% of lifetime operating costs for fossil fuel plants [119], these are negligible for renewable plant and thus fuel price volatility, an important element of risk (and an important determinant of discount rate) for fossil fuel plants, is irrelevant for renewable plant. This aspect is fundamental to the author's own analysis as has already been discussed in Section 1.3.3.3 and will be further explored in Section 3.4.

Two final areas of research in the field of capital budgeting are discussed here for the sake of completeness although these have not been applied in the current model; these are real option theory and portfolio theory. As was stated previously in Section 2.6.4 and as shown in Figure 2.19, synergies might exist between projects which serve to increase the overall value of a portfolio of investments. At some fundamental level this might simply be operational synergies, for example if two projects require the same infrastructure this might lead to lower costs through better utilisation rates, or two products may use the same sales channel which can be leveraged to deliver greater overall sales. However, synergies could also take other, more subtle, forms.

One such synergy might be the reduction of risk through production diversity which underlies the research into multi-variate portfolio theory (MVPT) [120]. In fact, while MVPT is introduced here as a standalone concept, it is in fact one of the key theoretical underpinnings of the CAPM, describing how in the presence of a portfolio of investments the risk is reduced to the non-diversifiable element [121]. In much the same way that holding a portfolio of securities with differing volatilities can reduce the overall riskiness of the set of holdings so, it is argued, a company pursuing a set of investments which are similarly uncorrelated (or partially correlated) can reduce the overall risk of those investments. While of undoubted interest as a theme in investment theory it was felt beyond the scope of the current study and hence no recognition of this is taken in the author's value maximising model. However, the concept is not entirely absent from the analysis since part of the utility of the author's model is to explore the price arbitrage benefits of an electricity utility investing in hydrogen production infrastructure, as will be discussed in Section 5.2.3.

Another area of research that started to gain currency in the 1990s is the concept of real options [122]. Options over securities or commodities have been utilised in hedging strategies and traded on defined markets for many years but the concept of real options is typically applied to investment decision-making. Essentially real option theory represents a method for valuing flexibility and is commonly utilised when the act of making one investment creates the opportunity (or option) to make a follow on investment. Botterud [123], for example, has used the principle to value the opportunity to produce either electricity or hydrogen directly from a nuclear plant. The investment would be assessed today on the basis of supplying electricity using traditional NPV analysis while the opportunity to produce hydrogen, should that market present itself in the future, is valued as an option. This could also be viewed as a synergy between projects with one allowing the option to invest in another. While of some significant interest as a method, option value is only considered in a qualitative sense in the current study not least because it is difficult to utilise in practice. The author's model instead concentrates on the basic principles of NPV and the earnings impact of making capital investments and largely ignores the additional value that might be attributed to these features of certain investments.

#### 2.6.4.2 Capital raising and the propensity to invest

While the author's model as developed currently assumes that capital would be available at a certain price to fund the investments envisaged, it is worth touching briefly on the literature surrounding factors determining the raising of capital and the propensity of companies to invest. Two concepts that have been widely reported in the literature that are pertinent to the current analysis are those of optimal capital structure and earnings per share dilution.

The first concept states that in the absence of taxes and the risk of default on loans a firm should be indifferent as to the proportion of equity and debt in its capital structure [124]. However, in the presence of taxes and where interest payments offset taxable profits a "tax shield" is created [115], encouraging firms to increase the proportion of debt in the capital structure. This is balanced by the fact that the risk of default and the cost of debt increases with leverage, thus acting as a brake to increasing debt. In consequence, as Stiglitz [125] observes:

"The crucial fallacy [of the Modigliani-Miller equation stating the indifference to capital structure] lies in the implicit assumption that...bonds a firm issues when it has a low debt-equity ratio and those which it issues when it has a high debt-equity ratio are the same. But they are not. They give different patterns of returns. If there is any chance of default, a bond gives a variable return..."

Any increase in the risk of default on debt in turn impacts the returns available to shareholders as well as bondholders and influences the value maximising behaviour of management as has been discussed, for example, by Baron [126].

The second concept centres around the relationship between capital raising and a company's earnings per share (EPS) and the resultant effect on share price. As Ohlson and Juettner-Nauroth put it in their 2005 paper [127] entitled "Expected EPS and EPS growth as Determinants of Value":

"A central organizing principle in practical equity-valuation focuses on firms' near term expected eps and its subsequent growth...[reducing stock valuation] to the idea that investors want to buy future earnings ''as cheaply as possible'' for a given risk-level."

The corollary of this is that the if the return per share is governed by the level of profitability and the number of shares in issuance, any increase in the firm's capital must bring with it a commensurate increase in profitability if the share price is not to suffer. To put it another way, any new investment must increase earnings per share (or at least expectations of eps) since, if this is not the case, the capital raising is *dilutive*, and there is an implied reduction in the return on equity and hence share price.

Ohlson and Juettner-Nauroth define the value of a company's share at time t = 0, $P_0$, in relation to the expected future earnings per share and dividend per share as shown in Equation (2.3).

$$P_0 = \frac{eps_1}{r} + \sum_{t=1}^{\infty} R^{-t} z_t \qquad \textbf{(2.3)}$$

where $z_t$ is defined as:

$z_t \equiv \frac{1}{r}[eps_{t+1} + r \times dps_t - R \times eps_t]$ for t = 1, 2, ...

and

$eps_t$ = expected earnings per share in period t, in currency units
$dps_t$ = expected dividend per share in period t, in currency units
r = R – 1 = Cost of Capital or Discount Rate, as a fraction

(thus $R^{-t} = \frac{1}{(1+r)^t}$ otherwise referred to as the discount factor)

Another way of looking at this would be to consider the price at which capital can be raised. The more cheaply (from the company's point of view) that new equity can be raised the lower the dilutive effect on earnings per share and the lower the risk of adversely affecting share price. This can be shown to be equivalent to the first statement since the absolute value of the price earnings ratio should reflect all market knowledge about the future prospects for the business including the profit streams expected into the future [128]. This is defined in Equation (2.4).

$$\Delta S = \frac{K}{P} \tag{2.4}$$

where

ΔS = new shares issued

K = capital raised, in currency units

P = price per share, in currency units

P can be rewritten as:

$$P = pe \times E$$

giving

$$\Delta S = \frac{K}{(pe \times E)}$$

where

pe = price earnings ratio

E = expected earnings, in currency units

Clearly for constant E the greater the value of pe the fewer the number of new shares issued and the lower the dilution experienced by existing shareholders. The reason this is of interest is that by observing the price earnings ratios across the sectors of interest to the author it is possible to detect discrepancies and it is argued elsewhere in this Thesis that a company might be more likely to invest if its own price earnings ratio is high, or if the price earnings ratio that is applied to the business being financed is high.

The connection between optimal capital investment, capital stock and equity returns has been explored by, among others, Porter [129] who has proposed that the firm value maximisation problem connects the production function, labour costs, investment and capital stock as shown in Equation (2.5).

$$V(0) = \sum_{n=0}^{x} \frac{y_n(k, l, i) - i_n - l_n)}{(1 + r)^n} \quad \textbf{(2.5)}$$

where

*V(0)* = Value at time zero, in currency units
$y_n$ = production output at time t = 0
$i_n$ = level of investment, in currency units
$k$ = stock of capital, in currency units
$l_n$ = labour cost, in currency units
$r$ = discount rate, as a fraction
$n$ = activity n of x

$V_{max}$ is found by taking the partial differential and is found to be the point at which the expected marginal benefit of an investment equals the expected marginal costs. A firm may decide that it can increase its level of capital stock in order allow an increase in investment dependent on the cost of that additional capital. The availability of capital will be a function of a number of factors but will essentially be driven by the classic supply and demand curve as shown schematically in Figure 2.20.

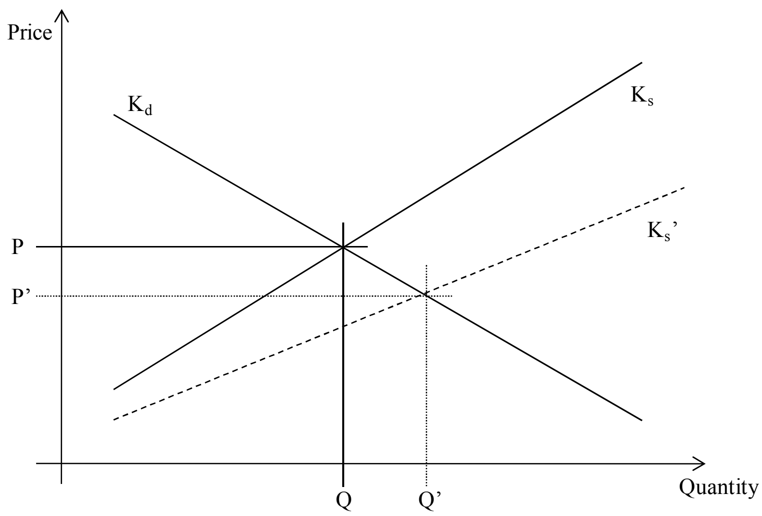



**Figure 2.20 Pricing of Capital Determined According to Supply and Demand**

The price refers to the return achievable to the provider of the capital (the investor) or the cost of capital if viewed from the perspective of the company raising money. The quantity of capital available will reflect the balance between the supply of capital ($K_s$) and demand ($K_d$), that is to say an amount Q at a price P.

In reality, for the purposes of this model it is assumed that there is no constraint on the supply of capital but as Figure 2.20 shows there is an implied relationship between the cost of capital and the supply or demand. Consequently policy measures are considered in the analysis which either increase the supply of capital for a given price or decrease the price for a given level of supply. This would be represented by a flattening of the supply curve from $K_s$ to $K_s$' as shown in Figure 2.20 with more capital Q' available at a lower price P'. In light of the significant squeeze on the availability of capital experienced during and since the credit crunch of 2008 onwards this factor is of particular interest.

### 2.6.5 Empirical Evidence for Cost Optimisation

Returning to the issue of whether in privatised energy markets there will be a general trend towards the lowest cost solution, in this section pertinent aspects of the empirical evidence are discussed.

If it is assumed that the cost of an energy system will trend towards its minimal point (as cost-optimising models hypothesise) this implies that each company in the sector will itself strive to minimise its own costs. All things being equal, the lower a company's costs the higher its profitability and thus a cost-minimisation strategy would be consistent with the profit maximisation function proposed by Jorgenson et al (see Equation (1.1)) and discussed in more detail in Section 3.4.2. However, it is also evident from Equation (1.1) that a company seeking to maximise value could also do so by increasing revenues, unless it was limited from doing so by market factors. It is reasonable to assume that inherent in the cost-optimisation model is the premise that the revenue maximisation strategy is indeed limited by the commodity aspects of energy pricing. To put it another way, price differentiation is the only strategy open to an energy company since demand will be determined principally on the basis of price. In order to satisfy the value maximisation condition, and in the face of competition, a company will be "forced" to lower prices to grow or sustain revenues (or, alternatively market share) and, by extension, reduce costs by a commensurate amount to sustain profit margins. It follows that, if both revenue maximisation or cost minimisation strategies are open to a company, the singular objective of cost reduction becomes less relevant. In order to explore this issue further, the literature surrounding energy price elasticity has been analysed and aspects of it are discussed here. In addition, the literature on the pricing of fossil fuels has been investigated to understand to what extent the market, in this case, for oil has trended towards least cost. Needless to say, in common with all goods and services markets, it is true up to a point that price plays a role in determining energy demand. However, empirical evidence does not support the view that price is the only determinant of demand, undermining the hypothesis that companies will invest in such a way as to reduce costs according to the argument made in the previous paragraph.

*Price Elasticity of Demand*

Research into price and income elasticities of demand for fuels in the UK carried out by Hunt and Manning [130] paints a picture of low price elasticities. According to their analysis, which covers the period from 1967 – 1986, short-term price elasticities of demand for a basket of fuels were -0.13 with long-run elasticities somewhat greater (-0.33) in magnitude (see Table 2.12). As the paper points out:

"...the effect of a change in the real price of energy is less in the short-run than in the long-run...[which] may...reflect the fixed nature of the machine and appliance stocks...[since] a rise in the real price of energy produces a modest fall in consumption in the short-term."

The incidence of low demand elasticities is confirmed by similar research carried out into the demand for transport fuels [131] by Dargay and Gately for the period 1962 – 1990. Once again, this research provided evidence that the short-run elasticities trend towards zero and, furthermore, that they demonstrate hysteresis with demand falling more quickly in the face of large price increases than they recover in the face of price falls (see Table 2.12). To put these figures into perspective, the same study found the income elasticities of demand to be 0.34 and 1.13 in the short and long-term respectively.

| | **Short-term elasticity of demand** | **Long-term elasticity of demand** |
|---|---|---|
| Price (all fuels) | -0.13 | -0.33 |
| Income (all fuels) | 0.45 | 0.70 |
| Price (transport fuels) | -0.04 | -0.13 |
| Income (transport fuels) | 0.34 | 1.13 |

**Table 2.12 Short and Long-term Price and Income Elasticities of Demand for Fuels**

This price elasticity data seems to suggest that at least over the short-run, the importance of price in determining demand is perhaps not as significant as might be believed and tends to weaken the argument that companies would focus on minimising price and, by extension cost (although this does not obviate the competitive pressures). Dargay and Gately point out that:

"The evidence that demand responds less strongly to price cuts is good news for transport policy: once a reduction in demand is attained, it will not be fully reversed if real prices fall again. The need to maintain a very high real price level may not be necessary. However, the effects of income growth can easily erode the effects of price rises, so that prices will need to rise more rapidly than incomes if fuel demand is to remain at a given absolute level."

However the corollary to this is that the hysteresis effect means that there may be little incentive for companies to reduce prices as a means to, for example, gain market share since reducing prices is unlikely to have an appreciable effect on demand. Interesting complementary evidence is provided by an examination of the data on the relative price of transport fuels within a 10 mile radius of the author's home in Glasgow (see Table 2.13).

| | Unleaded | | Premium Unleaded | | Diesel | |
|---|---|---|---|---|---|---|
| | *P / l* | *% ± mean* | *P / l* | *% ± mean* | *P / l* | *% ± mean* |
| **High** | 122.9 | 5% | 131.9 | 4% | 129.9 | 9% |
| **Mean** | 117.0 | - | 126.9 | - | 119.3 | - |
| **Low** | 113.9 | -3% | 123.9 | -2% | 116.9 | -2% |

*Source: petrolprices.com*

**Table 2.13 Transport Fuel Prices in the Glasgow Area July 2010**

What these figures reveal is that there is a variation in price of between 8% and 11% for the same product and that this rises to a figure of 16% between the high price for premium unleaded and the low price for regular unleaded. While this says nothing about the price elasticity of demand, since the quantities of fuel sold at these prices is unknown, it does suggest is that there is scope for price differentiation even for fuels as commoditised as petrol and diesel. The differences may be explained by factors such as brand loyalty, refuelling station location or station facilities and reinforces the view that price is not the only factor governing product choice, weakening the cost-minimisation argument.

In addition to the evident price differentiation that exists in the fuels markets today, a number of researchers point to a possible shift in the attitudes of consumers underpinning the deployment of alternatives to fossil fuels and in particular hydrogen. In such a scenario, differentiation of fuels on the basis of ‘‘greenness’’ may be possible with consumers willing to pay more for greener fuels as Barreto et al discuss [132].

*Oil price behaviour – Evidence of oil price decline?*

As has already been discussed, in a competitive market, it might reasonably be assumed that the price of a given energy source would converge with the underlying long-run cost defined as production cost plus a ‘‘satisfactory’’ return to the producer. However, it has been observed that the short-run prices of fossil fuels, perhaps most notably oil and gas, appear to bear little relationship to the underlying cost of production.

Considering the nominal prices in the two most recent periods it can be seen that whereas in the 1990s the oil price did not rise above \$25 per barrel, in the most recent years (2000 – 2009) it never fell below \$25. If confirmation were needed that the price of oil bears little or no relation to its cost of production, then these statistics seem to confirm the point since unless there has been a sudden and dramatic increase in the cost of production of oil it can only be assumed that oil was being sold at a loss in the 1990s or that the industry is extracting significant rents today. Current estimates of the marginal cost of production of crude oil vary by country and method of extraction, but the IEA put the figure for conventional oil at US\$30 – 40 per barrel [133] in November 2008, and this is not reflected in the price. It has been hypothesised by Griffin and Treece [29] that the marginal cost of oil production can be broken down into two elements, namely the conventional Marginal Production Cost (labour, materials) and the User Cost defined by Equation (2.6):

$$User\ Cost = Increased\ Security\ cost + Royalties + Extraction\ Cost \qquad \textbf{(2.6)}$$

While this may provide a partial explanation for the sustained high oil price regime it seems unconvincing given wide variations in price. Such short-run decoupling of cost and price is frequently observed in commodity markets where unexpected supply downturns (e.g. a border dispute, as was the case between Russia and Ukraine between 2005 and 2009) or demand upturns (e.g. increased heating requirements owing to unseasonably cold weather) lead to price increases as demand (in the first case) or supply (in the second) fail to adjust quickly enough. However, over the longer term these discrepancies should readjust and there is no evidence to show that it has, which weakens the cost-optimisation motive. What is clear is that the volatility and persistent underlying increase in oil prices are unlikely to provide the kind of environment that would lead companies to invest heavily in reducing costs.

So, while it is intuitively appealing to assume that energy companies will primarily pursue cost reduction strategies, in light of the commoditised nature of energy markets, the evidence for such behaviour is weak. By focusing on possible value creation opportunities open to the companies in the sector, the author's model allows for the possibility that companies will either strive for cost minimisation or revenue maximisation or, indeed, a combination of the two which is by far the most likely scenario.

## 2.7 Chapter Summary

It is clear from the discussion in Section 2.1 that the UK faces a number of serious challenges as it attempts to manage its energy infrastructure. The near "perfect storm" created by a high reliance on potentially insecure sources of fossil fuels, declining production of oil and gas from the UK Continental Shelf and the demands implied by emissions reduction have created an unusually turbulent environment. At the same time opportunities present themselves to create wealth through the development of new technologies and services in the energy field. One such opportunity lies in the development of hydrogen energy technologies which, it has been argued, have the potential to replace the use of fossil fuels in certain applications, increasing supply security and reducing carbon emissions simultaneously. The UK possesses many skills pertinent to the development of hydrogen and fuel cells technologies (see Table 2.10) but how the benefits of implementing this and other low carbon technologies can be assessed is hampered by the modelling techniques being used. The review of the extant literature provided in Section 2.6 offers clear evidence of the reliance on cost-optimisation techniques which are perhaps better suited to a planned energy environment. In order to better assess both the likelihood of private companies investing in new technologies such as hydrogen and to better understand the potential benefit to the economy of doing so, it has been argued that alternative models are required. A more recent body of literature confirms this view and underpins the development of author's model. Critical issues include the need to recognise not only the basic underlying costs of systems but the possible revenue streams and, critically, the relative riskiness of one set of investments versus another. Fossil fuels are commodities and have proven to demonstrate highly volatile prices. If renewably produced hydrogen can be used to reduce the effects of price volatility in the energy markets then, it might be argued, the benefits go beyond those of increased supply security and emissions reduction.

Nevertheless, despite the potential benefits that hydrogen energy could represent, there are significant barriers to the implementation of widespread hydrogen energy infrastructure, even if its added value could be demonstrated through the type of modelling proposed by the author (see Section 2.5). These barriers include the fact that hydrogen requires significant input energy to produce, partially undermining the benefits to be gained by its use in fuel cells, it is difficult to store and to tranship leading some observers to view it as technically inferior to other solutions proposed.

In this Chapter the following subjects have been covered:

- A brief review of the energy industry in the UK covering aspects such as the energy mix, degree of energy independence and reliance on fuel types as well as the country's reliance on different fuels. It has been shown (see Figure 2.3) that the UK has a heavy reliance on fossil fuels (>90%) but that it currently enjoys a partial hedge through its own supplies of oil, gas and coal (roughly 90%). This hedge however is declining in coverage.
- In Scotland, depending on the way oil from the UKCS is treated and decisions which will be taken over nuclear power demonstrates either slightly superior or significantly superior energy security than the UK taken as a whole. This is in part due to its excellent renewable energy resources, especially wind and wave.
- An analysis was provided in Section 2.2 of the impact of the energy industry on the economy including the size of the energy spend by consumers, its GDP contribution and position as a savings repository. From the analysis it can be seen that energy represents 5 – 10% of GDP and that the energy sector represents a repository for approximately £185bn of savings, roughly equivalent to the annual savings rate.
- Reference was made to the level of the UK's $CO_2$ emissions by different measures revealing that the UK is the world's $7^{th}$ largest $CO_2$ emitter (540 million tonnes annually). It has average $CO_2$ emissions per capita and emissions intensity compared with its European peers (see Figure 2.6).

- A brief description of the current policy measures in place to shape the energy industry, as government attempts to achieve its goals of carbon reduction and energy security, was provided in Section 2.4. This confirmed that although currently there is a combination of demand side (e.g. climate change levy) and supply side (e.g. Renewable Obligation) measures, the government expects the majority of carbon emissions savings to be delivered through the EU Emissions Trading Scheme.

- An overview of the role that hydrogen energy could play in the energy mix was offered (see Section 2.5) including a description of the characteristics of hydrogen as a fuel and how it could contribute to GDP. Hydrogen has the potential to be a carbon free fuel with zero emissions throughout the energy chain and high energy conversion efficiencies are possible through the use of fuel cells. However, hydrogen faces some significant barriers in terms of its introduction into the energy mix, notably the high energy input required to produce hydrogen and the difficulties in transporting and storing it.

- A review of the energy forecasting literature was offered, focusing on work in the hydrogen energy and electricity supply sectors as well as a review of the investment literature. This review confirmed the proclivity for the use of cost optimisation models amongst national and supra-national organisations. The review confirmed the novelty of the author's area of research work and provided the author with useful guidance in terms of the techniques employed.

# 3 Development of the model and its positioning relative to others

Section 2.6 provided a relatively broad description of the literature pertaining to energy modelling and how the current research fits within that body of literature. In this Chapter the author's model is described in detail and compared more directly with one particular branch of current modelling, namely the MARKAL cost-optimisation model. The reason for choosing MARKAL is its relative ubiquity and its similarity in modelling approach to other techniques. As was discussed in Chapter 2, numerous large scale studies have been performed using MARKAL and many common issues with the techniques can be highlighted with reference to this one model.

## *3.1 General Principles*

The value maximising model described here seeks to develop forecasts for future market development based around an analysis of the impact on the value of market competitors of investments in different energy infrastructure. The energy markets in the UK are now completely deregulated and while different government incentives and taxes can have a significant impact on the way the markets operate, it is ultimately the behaviour of individual companies that determines the way in which the market develops. For this reason, the author believes that a systems-based analysis might be misleading and has chosen instead to focus on what drives companies to invest in a given activity.

While a number of theories exist to describe or explain how companies go about making investment decisions as was discussed in Chapter 2, perhaps the most prevalent is the concept of agency, whereby the management of a company is expected to act in such a way as to maximise the value of that company's equity, i.e. shareholder value maximisation. Consequently, the model focuses on the shareholder value creation potential associated with different investment opportunities and, based on this, calculates possible market development pathways.

What factors determine the value of a given share of equity has been a matter of some debate (see Section 2.6.4), but a certain amount of consensus exists and the model described here uses three commonly accepted methodologies for calculating a company's value as will be described in Section 3.4.

## 3.2 Comparison with the Cost Based Approach

The key features of the cost-led and investment-led models are shown diagrammatically in Figures 3.1 and 3.2. Under the systems-based cost-led approach, infrastructure is added according to least levelised cost, with systems having lowest cost, i.e. System A, being added first, next lowest (B) second, and so on until there is sufficient capacity to meet demand. This is illustrated in Figure 3.1 where systems A to D are deployed in order to meet demand according to relative cost, where the levelised cost of each system is as defined by the inequality shown.

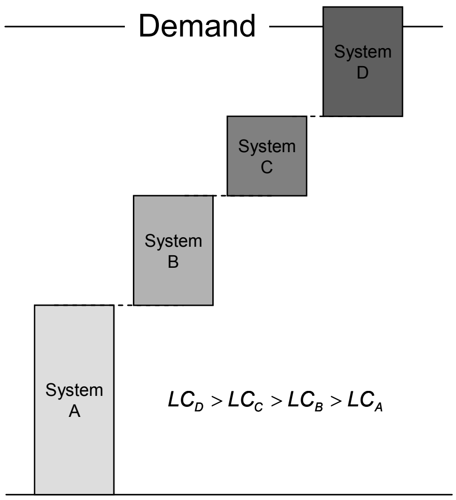



**Figure 3.1 Simplified Schematic Representation of Cost-Led Approach**

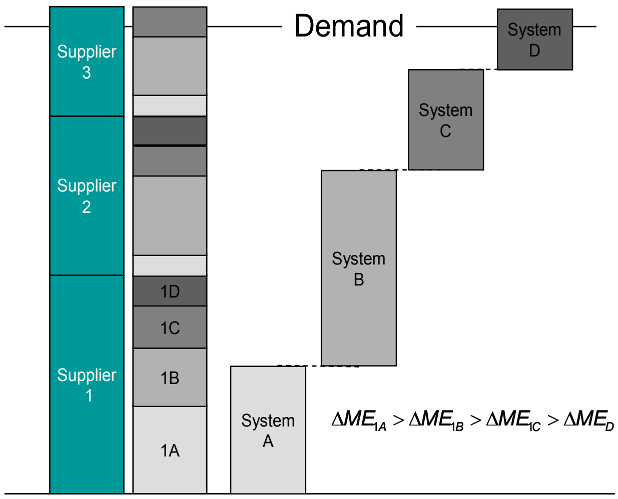



**Figure 3.2 Simplified Schematic Representation of Investment-Led Approach**

By contrast, the value-led approach has the company rather than the system as its starting point as is detailed in Figure 3.2. Companies are either already present or choose to enter the market and each company makes decisions about the systems in which it will invest on the basis of the relative value added which each represents. The highest value added system is chosen first, which in the case of Company 1 is

System A, the second highest (System B) next and so on until its ability to add value or "financial capacity" is exhausted. Here the term value-added is expressed as the additional value contributed to the equity market value of the company ($\Delta ME_{xy}$), once again defined by the inequality shown. Companies 2 and 3 then select systems in the same way with the resultant set of infrastructure being the summation of the capacities deployed by each of the companies. Critically, whereas in the cost based model the ordering of the systems is a given, the value-led model allows for the possibility that the order and extent of investment will differ from company to company. Consequently, the investment-led model requires an understanding of what contributes to the value of a company's equity at time t ($ME_t$) which is defined by Equation (3.1).

$$ME_t = SP_t \times NS_t \tag{3.1}$$

where:

$ME_t$ = equity market value at time t, in currency units
$SP_t$ = share price at time t, in currency units
$NS_t$ = number of shares in issue at time t

In order to illustrate the differences that are apparent in the cost and investment led approaches it is helpful to consider a theoretical example. Figure 3.3 presents the cost-based view with regards to the timing of the introduction of hydrogen fuels into the energy mix.

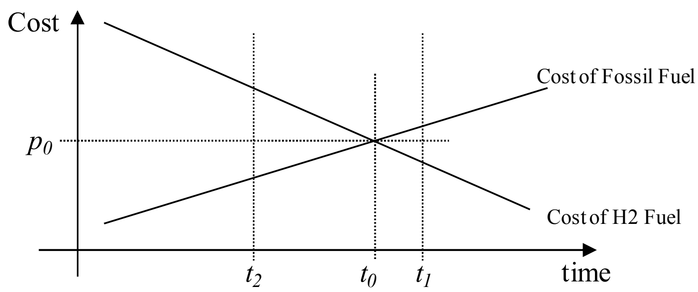



**Figure 3.3 Simplified Chart of Investment Timing as Determined by the Cost-based Approach**

It is assumed in this example that the cost of fossil fuels will increase over time whilst the cost of producing hydrogen has a tendency to fall as production efficiency improves, learning effects take hold and so on. At some point in the future, call it $t_0$, the cost of producing hydrogen equals that of fossil fuels and at this point it might be imagined that hydrogen would start to find favour over fossil fuels. Implied in this analysis is an equal cost of capital associated with the two systems which may not reflect the view of the potential investors.

Figure 3.4 on the other hand presents the same analysis but on the basis of returns to the companies in the market. Returns to fossil fuel companies are shown as increasing slightly owing to the increasing prices and relatively low price elasticity of demand. Hydrogen company returns are shown as increasing more rapidly reflecting the higher growth potential apparent with these technologies. Two different returns curves are shown in the example reflecting two different choices of cost of capital.

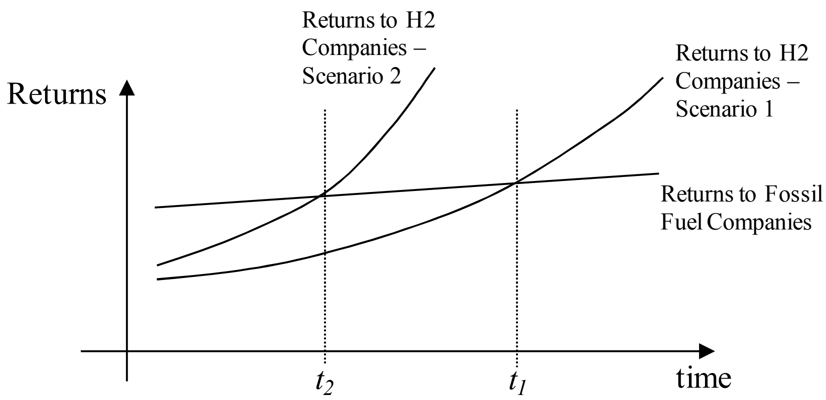
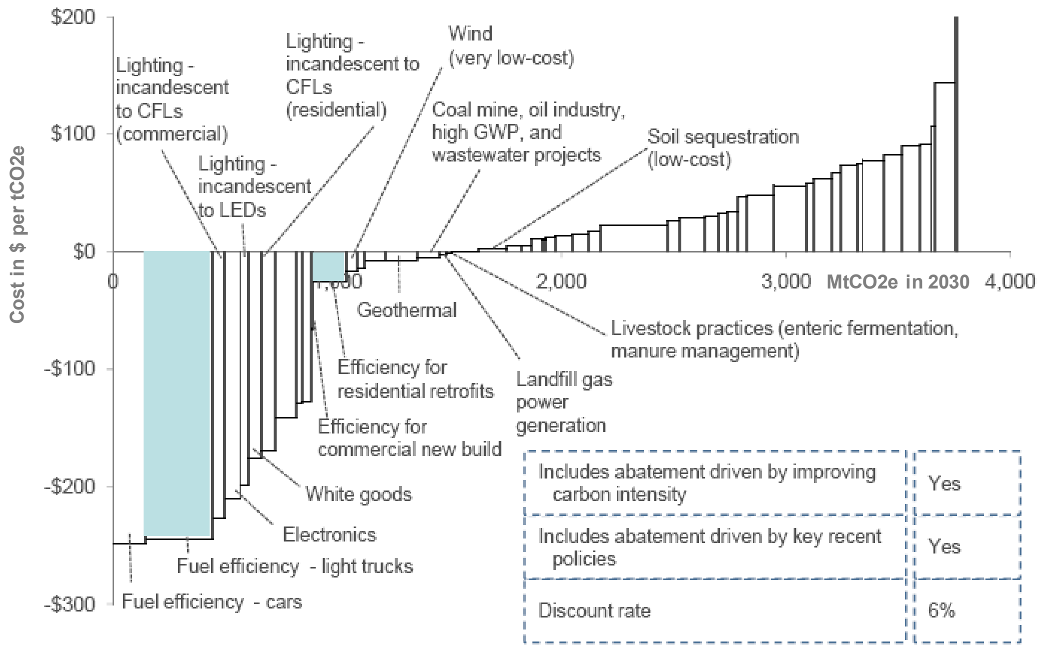



**Figure 3.4 Simplified Chart of Investment Timing as Determined by the Returns-based Approach**

The point at which investment would be switched from fossil fuels to hydrogen technologies would now be determined by when the investment becomes more attractive, in this case at times $t_1$ or $t_2$ respectively, which is in one instance earlier and in one instance later than $t_0$. Of course, a relationship exists between the cost and the returns but since cost is not the sole factor affecting the returns profile consequently an analysis of the returns aspects may render different results as shown.

Another way to think of the same issue is from the point of view of Marginal Abatement Cost (MAC) curves. These curves are designed to compare the cost effectiveness of different measures to reduce greenhouse gas emissions with the underlying principle being that from a societal point of view it is preferable to apply those measures which cost least first and then successively more expensive measures in turn as a function of their cost. A typical MAC curve is shown in Figure 3.5. The y-axis shows the cost of the abatement measure in US dollars per tonne of carbon dioxide emitted while the x-axis shows the cumulative amount of carbon dioxide that can be saved.




*Source: Bloomberg New Energy Finance*

**Figure 3.5 US Marginal Abatement Cost Curve for 2030**

If the two blue coloured bars are considered, the issues with applying a purely cost-based approach begin to become apparent.

Taking the question of vehicle fuel efficiency, the MAC is shown to be roughly -\$250 per $tCO_2e$. This implies that even if the cost associated with developing more fuel efficient vehicles is passed onto the end customer the savings to the customer significantly outweigh this additional cost, i.e. there is a win-win situation for both the vehicle manufacturer and the end-user. However, this raises some critical questions relating to whether, in a competitive new vehicle market, manufacturers would be able to pass on the cost of investing in vehicle efficiency to the end customer. If the price elasticity of demand for vehicles is relatively higher than for fuel then would manufacturers be able to increase prices to recoup their investment? Furthermore, even if it is assumed that buyers will make this sort of total cost of ownership (TCO) calculation, will they be able to make accurate predictions given the highly volatile nature of fossil fuel prices? Finally, what is the appropriate discount rate to choose? The discount rate is critical since this will affect the calculated cost for making the investment required to improve the fuel efficiency of vehicles manufactured and indeed the value of the eventual future fuel cost savings. The example MAC curve in Figure 3.5 assumes a 6% discount rate but many companies would demand a significantly higher rate for investment projects and individuals may each have different attitudes to risk.

Considering the case of Efficiency for Commercial / Residential it is clear that there is a cost associated with mitigation which must ultimately be borne by the end consumer. Consequently there is a potential hurdle to overcome in terms of encouraging the end user to pay for the efficiency improvement but there may also be an issue in terms of how the provider of the efficiency improvement is able to monetise its investment.

These simple examples help to highlight how the cost and value led approaches might differ in their outcomes and underpin why it is worthwhile pursuing the value-led model.

## *3.3 Description of the Functioning of the Author's Model*

The model is built in a number of phases and how it functions is perhaps best described with reference to the schematic in Figure 3.6. The period modelled runs from 2010 – 2050 which corresponds to the timeframes for the long range policy objectives at national and supra-national level. This implies that cashflows must be projected as far ahead as year 2050 plus the lifetime of the last project, which for the purposes of the current model is assumed to be a maximum of 30 years. Thus, revenues, profits and cashflows are projected forward up to 2090 and needless to say such long range projection presents its own issues in terms of data uncertainty. In consequence, a variety of approaches have been taken to model this uncertainty and to explore possible outcomes which are discussed in Section 3.5.3. Each phase of the model is described in the paragraphs following the figure.

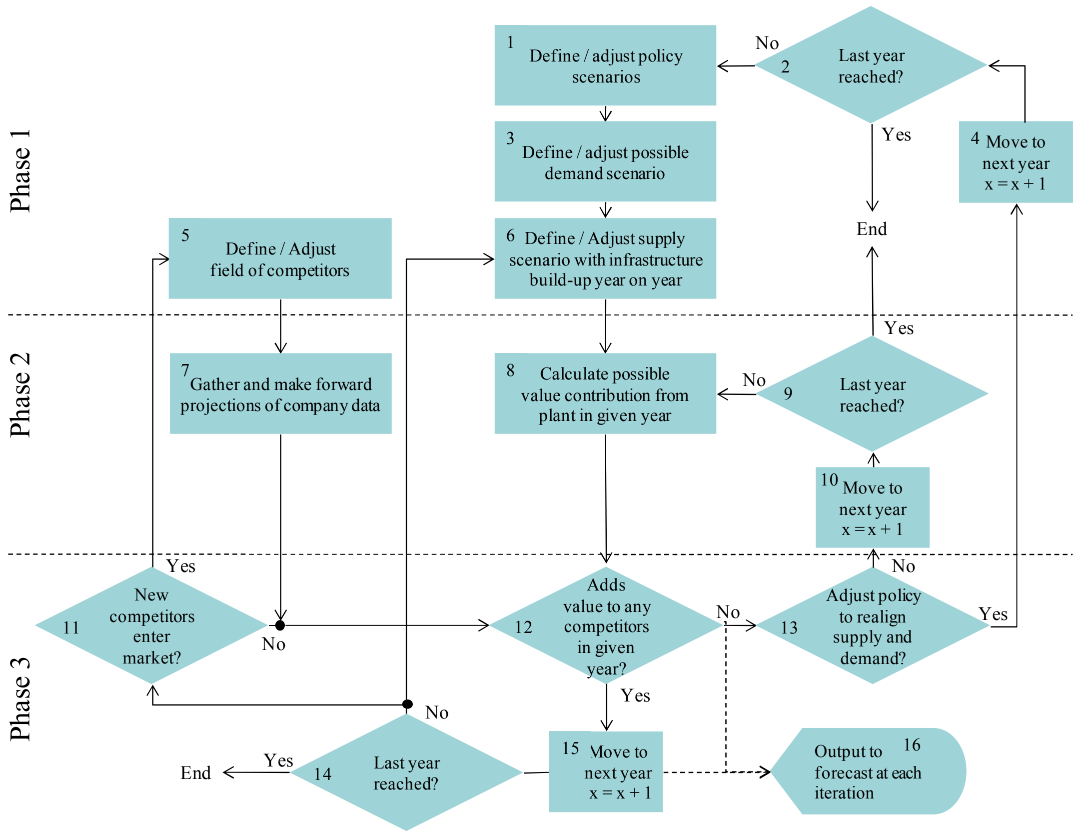



**Figure 3.6 High Level Schematic and Flow Chart of Author's Model**

**Phase 1: Definition of initial environmental and demand scenario**

Projections of energy demand by source (e.g. oil or natural gas) and vector (e.g. electricity or hydrogen) type are made based around initial expectations of overall growth, changes in demand patterns or a particular set of desired outcomes (Box 3). At the same time those policy or market incentives / disincentives that are designed specifically to affect company behaviour, including for example carbon taxes or feed-in tariffs, form a further input to the model (Box 1). A range of possible plant types capable of satisfying that demand is defined according to their cash-flow and profitability profile and capacity build-up is projected (Box 6). Since the model is concerned with the propensity of companies to invest in new plant so as to meet the supply function, the current and projected future financial characteristics, such as growth, margins, cost of capital etc., of the companies operating in the market (or that have the potential to enter the market) are input (Box 5). These and sector data are also gathered, projected forward into the future and input (Box 7).

**Phase 2: Examine possible value contribution from investment projects**

The model calculates the value-contribution that could be anticipated from each plant type (Box 8). The concept is illustrated in Figure 3.7 which shows two possible modules of the same type begun in two different years. Year 10 revenue and profitability data, say, is used together with NPV data to determine the possible value impact of the plant conceived in either 2016 or 2025 on a given company. Note that data from year 10 is suggested since this would be post the initial start-up phase when revenue and profitability performance should have stabilised.

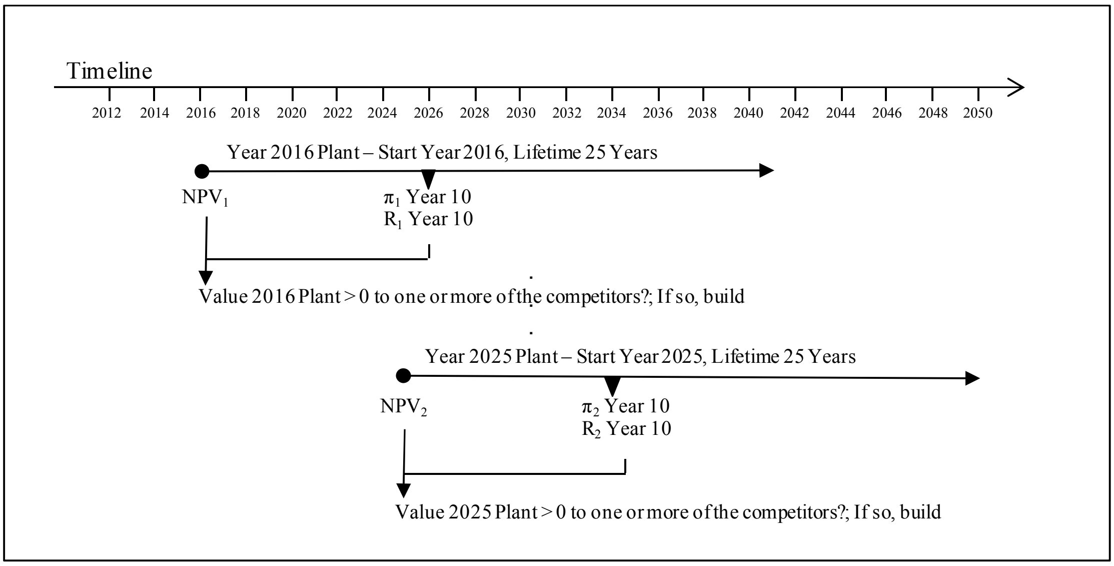



**Figure 3.7 Illustration of Plant Build Decision Process Incorporated within Model**

**Phase 3: Test likelihood of companies to invest in such projects relative to others**

The model then determines whether the projected plant can add value to each of the competitors based on the current and projected financial characteristics defined in

Phase 1 and according to the metrics in Section 3.4. As Figure 3.7 indicates, where a plant can show a positive impact on value of one or more competitor's in a given year then it is assumed that such plant will be developed in that year; if not, it is assumed that the plant will not be built as projected (Decision Box 12).

In the case that the output of the decision box is positive the number of plant assumed to be built is output to the forecast (Box 16) and the model moves on one year (Box 15). A check is made to see whether the final year in the forecast has been reached (Box 14); if so the programme ends, if not it returns to the supply forecast (Box 6) and performs the loop again. At the same time, the opportunity exists to look at and adjust the field of competitors (Box 11) and return to Box 5 or simply continue with the same field of competitors.

If on the other hand the output of decision Box 12 is negative the output is still sent to the forecast box (Box 16) but then a further decision box is entered (Box 13) which allows for the policy set to be altered. If the decision is taken by the user not to alter the policy set then the program returns to the main loop (Box 8) via the year move (Box 10) and Last Year query (Box 9). On the other hand if the policies are to be adjusted the program moves back to Box 1 via a year move (Box 4) and Last Year query (Box 2) where the forecast and policy metrics can be altered.

In this way, an "actual" plant build up profile is arrived at for each year of the analysis (2010 – 2050). It should be noted that if a particular type of plant is initially not viable it may be replaced by other types of plant which are or if that plant type subsequently becomes viable the opportunity exists to "catch up" to the initial forecast, within certain limits. If the demand forecast is conceived of as a desired outcome, then if plant is not being built at a fast enough rate to meet the desired level of demand because it fails to meet the investment criteria of the market competitors, then a government might want to adjust policy instruments to be more aggressive in order to return supply to the desired trajectory. This can be achieved in the model by altering the policy data on review of the actual plant build-out forecast by the model as shown here or periodically, say after every five year steps in the model, if desired.

## 3.4 Definition of the Objective Function

As has already been discussed in Chapters 1 and 2, given the role that company strategy plays in the development of a given market the model developed in this Thesis has the concept of company objectives at its core. The assumption is that a company will identify an objective function which it will seek to optimise through its strategic investments and, for the purposes of this analysis, it is assumed that the principal objective would be to maximise shareholder value. Once again, this objective could be met in a number of different ways and the underlying drivers of shareholder value are not entirely transparent. However, it is assumed that three reasonable underlying drivers would be the NPV of investments, the future profitability and the growth of the business.

### 3.4.1 Net Present Value

The value of a firm can be considered to be the sum of the Net Present Value (NPV) of all the projects it is undertaking at any given point of time as derived from Equations (1.2) and (1.3) and shown in Equation (3.2). Consequently, it may be assumed that any NPV positive project will contribute positively to company value and a company should seek to maximise its portfolio of NPV-positive projects subject to capital constraints and strategic concerns.

$$V(n,t) = \sum_{n=1}^{N}\left[\sum_{t=0}^{x}\left(\frac{CF_n(t)}{(1+r_n)^t}\right) + \frac{RV_n}{(1+r_n)^{x_n}} - I_n\right] \quad \textbf{(3.2)}$$

Where:

*V(n,t)* = value as a function of number of projects, n and of time, t in currency units

$CF_n(t)$ = Cash flow in period t to n$^{th}$ project (of N), in currency units

$r_n$ = Discount rate (or Expected Return) for n$^{th}$ project, as a fraction

$RV_n$ = Residual value at the end of the project, in currency units

$I_n$ = Initial investment for nth project, in currency units

$x_n$ = Lifetime of the n$^{th}$ project, in years

In calculating the NPV of any given project, the choice of discount rate (or cost of capital) is critical and should be related to the inherent risk associated with the project. It is typical for companies to use their own underlying Weighted Average Cost of Capital (WACC) as a basis for the discount rate and then to adjust it to reflect the perceived riskiness of the project [117]. As discussed in Section 2.5.7, it is hypothesised by the author that the inherent price volatility associated with fossil fuels should attract a higher cost of capital to fossil fuel activities. Conversely, for renewable energy systems and it is suggested that renewable hydrogen projects could attract a lower cost of capital thus making investments more favourable. A useful presentation of the possible risk factors associated with any given investment is offered by Wüstenhagen and Teppo [134] which is reproduced in Figure 3.8.

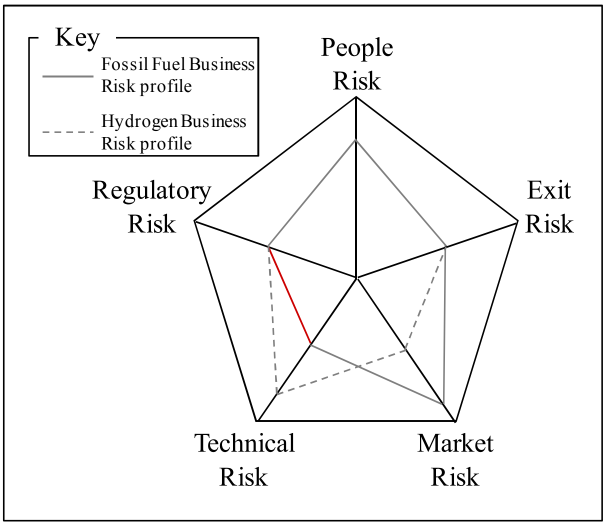



**Figure 3.8 Illustrative Risk Profiles of Companies or Projects to Supply Hydrogen and Fossil Fuels**

As Awerbuch surmises, a shift away from commodity fossil fuels having high price volatility might allow a lower discount rate to be employed. Using Wüstenhagen and Teppo's model, this might be recast as a shift from exogenous (in this case, market) to endogenous (for example, technical) risk factors which a company or investor might feel more able to manage and therefore apply a lower discount rate (see illustration in Figure 3.8). This factor is discussed further in Chapter 5 when describing the results of applying the model to the Scottish case.

### 3.4.2 Earnings per Share Impact

As long ago as the 1960s Jorgenson et al [15] advanced the view that the value of a company could be determined with reference to its future stream of after tax receipts – roughly equivalent to that company's cash flow – as shown in Equation (3.3).

$$V(t) = \int_{t=0}^{\infty} e^{-rt}[P(t) - D(t)]dt \qquad \textbf{(3.3)}$$

Where
V(t) = value as a function of t as before in Equation (3.2)
*P(t)* = Pre-tax cash receipts in period t
*D(t)* = Taxes in period t
*r* = Discount rate

Closely related to this neo-classical approach, the Earnings per Share (EPS) Impact model (or Accretion / Dilution model) is commonly applied by practitioners when assessing the impact on company value of raising capital or of making acquisitions. The concept is that, as in the neo-classical model where the value of a company is a function of future after tax receipts, the value can be related to the EPS (closely related to the after tax receipts). To put it another way, the value of the company can be thought to be determined by its return on equity which is defined by Equation (3.4).

$$ROE = \frac{E_t}{NS_t} \equiv EPS_t \qquad \textbf{(3.4)}$$

where:

*ROE* = Return on Equity as a percentage
$E_t$ = expected profit in period t in the absence of the project
$NS_t$ = expected number of shares in issue in the absence of the project
$EPS_t$ = expected EPS in time period t in absence of the new project, in currency unit per share

Thus, if an investment has a positive impact on EPS within a predetermined time frame (typically a number of years into the project once EPS has stabilised) this can be expected to have a positive impact on value and vice versa. The change in EPS (ΔEPS) is given by Equation (3.5).

$$\Delta EPS_t = EPS_t' - EPS_t \qquad \textbf{(3.5)}$$

where:

$EPS_t'$ = expected EPS in time period t including the new project, defined by Equation (3.6).

$$EPS_t' = \frac{(E_t + \Delta E_t)}{(NS_t + \Delta NS_t)} \qquad \textbf{(3.6)}$$

where:

$\Delta E_t$ = increase in profit attributable to the project
$\Delta NS_t$ = number of new shares issued in financing the project (if any)

Since the profitability of investment projects varies on a temporal basis it is useful to examine various aspects of project performance such as the period to reach positive profitability, maximum profitability or, as is presented here, the relative profitability in a given year of the project.

### 3.4.3 Multiples Analysis

Another common approach to valuation used by practitioners is multiples analysis whereby the value contributed by each activity in a company's business is calculated with reference to prevailing industry multiples, e.g. price to earnings ratio or enterprise value to revenues, applicable to that activity. The value of a company, *V(t)* undertaking a new activity either within or outside its core business can be calculated with reference to this "Sum of the Parts" approach as shown in Equation (3.7).

$$V(t) = [R(t) \times EVR(t)] + [\Delta R'(t) \times EVR'(t)] + [\Delta R''(t) \times EVR''(t)] + \cdots \quad \textbf{(3.7)}$$

Where

*R(t)* = Expected revenues from core business in period t

*EVR(t)* = EV / R ratio associated with the core business in period t

*ΔR'(t), ΔR''(t)* = Increase in revenues associated with new projects, in currency units

*EVR'(t)* = Price Earnings ratio associated with the first new business in period t

EVR''(t) = Price Earnings ratio associated with second new business in period t, etc

The underlying concept is that in perfect markets investors attribute a value to companies in a given sector based on all information relating to the future performance of the company itself and the sector in general. In effect, investors are themselves estimating the discounted value of the future stream of after tax receipts and applying a value accordingly or, to put it another way, it is an empirical approach to calculating value as opposed to one based on specific forecasting.

### 3.4.4 Definition of the Solution and Constraints

If Equations (3.2), (3.4) and (3.7) represent the primary objective functions for each company addressing the hydrogen and fuel cells market, then the optimal solution, which maximises the value of a given company would normally be given by taking the first derivative and setting it to zero if the function is not monotonic. As was seen in Section 1.4.1, the objective function can be described by Equation (1.8) which is repeated in Equation (3.8).

$$ME_{t=1} = SP_{t=0} \times r(I_t) \times NS(I_t) \quad \textbf{(3.8)}$$

As before, the maximisation function would then be described by setting the first order derivative to zero but in fact the model does not attempt to solve for this differential but rather is used to observe trends and to make comparisons rather than to arrive at a single optimal point. Each company will be subject to a number of important internal and external constraints which can be described by inequalities. The constraints and associated inequalities are described in Table 3.1.

| Constraint | Description | Inequality |
|---|---|---|
| **Maximum leverage** | Maximum permitted ratio of debt to equity. This is maintained below maximum level in order to ensure maintenance of credit rating and prevent the firm from experiencing undue financial strain. The base case value for $L_{max}$ is determined with reference to empirical industry average values but can be varied by the user. It should be noted that the French Fama relationship referred to in Equation (1.7). suggests that the returns to a company's equity will be influenced by the degree of leverage but since the exact relationship is unknown this aspect is modelled through the application of a maximum limit on leverage. In effect an algebraic relationship is replaced by a binary one with the assumption being that when $L_{max}$ is exceeded then there will be negative impact on value whereas if a company works within the bounds then there will not. | $\frac{D}{E} \leq L_{max}$ |
| **Maximum exposure to one business activity** | Maximum permitted ratio of sales of one activity relative to the total revenue of the company. Recognising the potential increase in risk associated with business concentration and the converse reduction in risk through diversification. Once again this could be captured in the discount rate but this limit is introduced to reflect the likely strategic management decision to limit business concentration exposure. The limit is set according to the user's choice since this limit is not the subject of empirical analysis. | $\frac{R_x}{R_{Total}} \leq W_{max}$ |
| **Maximum equity fund raising** | Maximum permitted additional equity capital that the company can raise relative to the current level of equity in the firm. While the dilutive effect of equity fund raising is captured in the objective (3.5) a further limit imposed to reflect the likely openness of the market to multiple fund raisings in a given period whether these fund raisings are accretive or not. The argument is that there is a potential negative impact and cost associated with repeated fund-raisings. The average number is set according to empirical evidence of the number of fund-raisings. | $\frac{NS}{S} \leq D_{max}$ |
| **Maximum total investment in given period** | Limits the total funds that can be invested by a given company. Once again, companies will typically place strategic limits on the amount of capital investment and the value of $I_{max}$ is user set. | $I_{Total} \leq I_{max}$ |
| **Minimum investment size** | Maximum and minimum limits on the size of individual investments that a company will undertake. The maximum reflects the strategic desire not to undertake too large investments – companies will typically have an investment size they are "comfortable" with. The minimum reflects the fact that there are transaction costs associated with pursuing a particular investment and smaller investments may not be considered cost effective even if NPV positive. The base case minima and maxima are defined with reference to the size of the company making the investment. | $i_{max} \geq i_x \geq i_{min}$ |

**Table 3.1 Internal and External Constraints Contained within Model**

### 3.4.1 Some Simplifications

There are two important simplifications inherent within the author's analysis. The first is that the current model does not develop a full demand side "forecast". As has been described in Section 1.4.2, a possible picture of future demand is utilised based upon an extrapolation of historical demand patterns coupled with a set of assumptions about the relative likelihood of take-up of applications requiring different fuels. While it would have been entirely feasible within the structure and terms of the model to build the demand side using the same value-maximising approach, this was considered too complex within the timeframe available. The second simplification is that the analyses presented only consider the relative attractiveness of electricity and hydrogen. While the facility exists within the model to evaluate the performance and impact on value of multiple fuels and vectors, the particular remit of the project's industrial partner, an electric utility, meant that the author was most concerned with evaluating the relative merits of these two energy vectors. In addition, this allowed the specific issues relating to the disruptive nature of hydrogen as an energy vector to be explored and discussed.

## *3.5 Implementation of the Model in Software*

### 3.5.1 Modelling Environment

The author's model is built as a series of worksheets within an Excel Workbook upon which a series of Macros programmed in Visual Basic (VBA) perform functions and create data in further worksheets. Spreadsheets are an ideal way to perform repeating functions, for example, on multi-year data. The ability to combine the spreadsheet functionality with macros provides a high degree of flexibility and offers a cost and time efficient way to derive results. The charting functionality of Excel further allows the rapid interpretation and display of results for the user. Each of the worksheets has a particular function within the overall model and each of these is briefly described in Table 3.2. Screenshots of example worksheets are shown in Figures 3.9 and 3.10.

| Sheet Name | Function in Model |
|---|---|
| Assumptions | Provides current and projected data on a number of fundamental, mostly exogenous, economic variables |
| Policy Data | Provides current and projected data on policy instruments and levels of support for low carbon technologies |
| Adoption Curves | Contains data necessary to the construction of the energy demand S-Curves |
| SG Demand Data | Collates all the current and projected energy demand data from the Scottish Government report [24] |
| End-User Demand Forecast | Provides application level demand projections based on the core "hydrogen plus electricity" scenario |
| Primary demand Forecast | Provides primary level demand projections based on the core "hydrogen plus electricity" scenario |
| Capacity Build-Up | Provides a projection for the required plant necessary to fulfil the primary demand forecast |
| Capital Cost Evolution | Provides projections for the capital cost of plant variants according to Equation (3.10) |
| Price Scenarios | Provides projected pricing data for energy and fuel types |
| Modules Sheets (Hydrogen, Electricity, Biofuels, Renew / Heat, NG, Oil | Provides core data on the different plant types as well as being the sheet in which the pro-forma P&L data is input and the NPV calculated |
| Company Data | Provides overview performance, financial and returns / valuation data for all investor companies considered in the analysis |
| Company Sheets | Sheets corresponding to each of the investee companies and used to record value-contribution data when calculated. |

**Table 3.2 Description of Core Worksheets Making up Model**

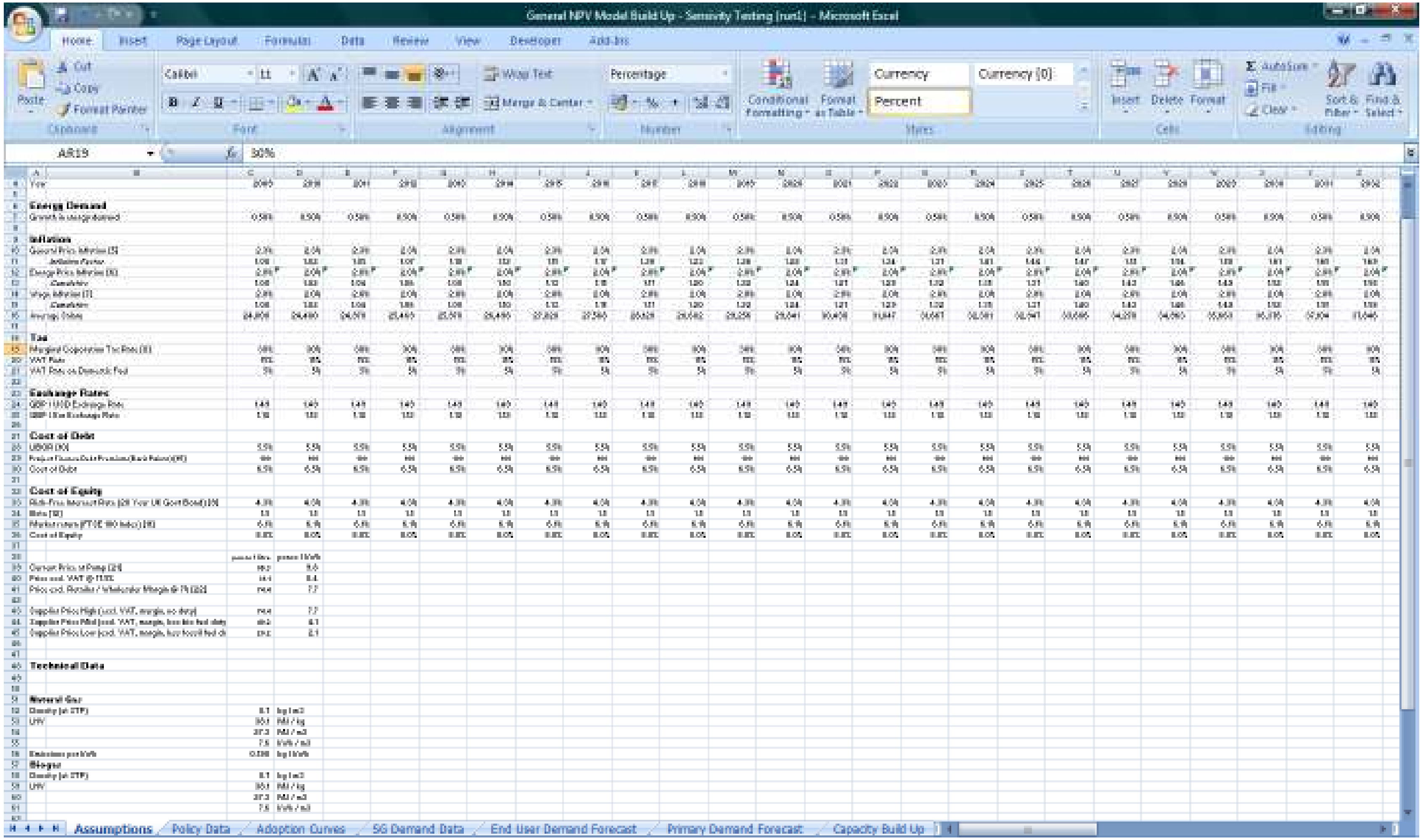



Figure 3.9 Screenshot of Assumptions Worksheet within the Model

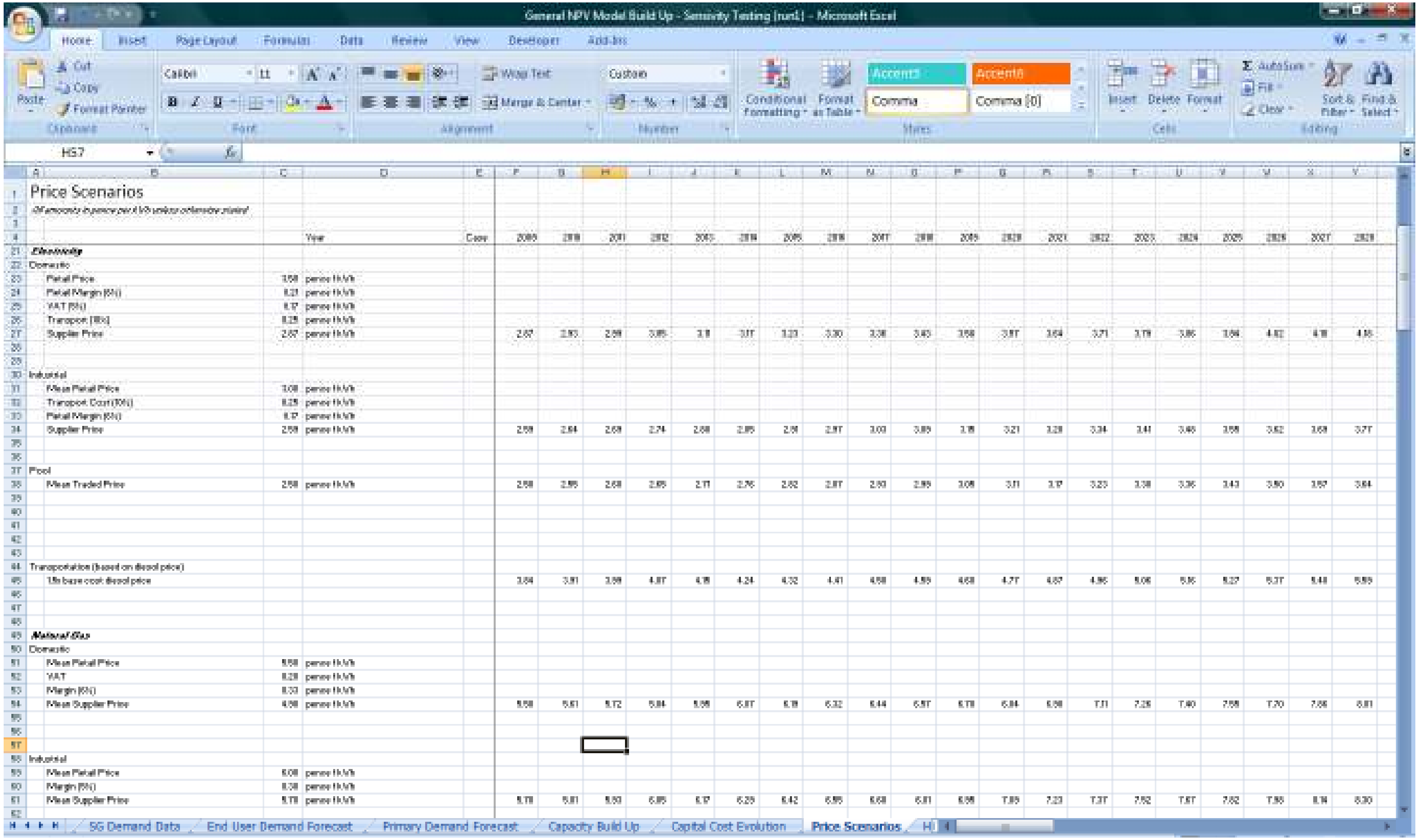



**Figure 3.10 Screenshot of Price Scenarios Worksheet within the Model**

The engine of the model lies in the series of "Modules" sheets which calculate the underlying characteristics of each of the types of plant envisaged by the model and projects these forward. These sheets draw data either directly, through Excel functions, from other sheets in the Workbook or through Macros. The calculation of key line items in the P&L associated with each "project" is performed by a Macro drawing data from this sheet and others. The P&L data is stored in an array and is retrieved by other Macros which perform sensitivity and Monte Carlo analyses based around input parameters such as fuel costs or discount rate. Example code for some of these Macros appears in Appendix 7.1.

### 3.5.2 Software Flow Charts

The model implementation is best described through the use of flow charts representing the different operations. In essence the model works through a series of nested loops each performing a different set of calculations contributing to the overall solution. The principal cycles are pictured in Figure 3.11 and described below.

Moving from the outer loop inwards, the macro starts by accessing the first of the module sheets (usually hydrogen modules) and will then move through each of the subsequent module sheets once the other loops have been completed. The macro next accesses the first of the company specific sheets and stores data relevant to the value calculations in an array. The macro subsequently moves through each of the companies in turn once the other loops have been completed. The value calculations will then be made for each plant type successively as the program moves through the each plant type in turn. At the core, the program carries out the value calculations for each plant and year between 2010 and 2050 (i.e. each "Project Capsule") which in turn requires the calculation of the revenues, profits and cash flows for each year through the lifetime of project. This is achieved by the innermost two loops.

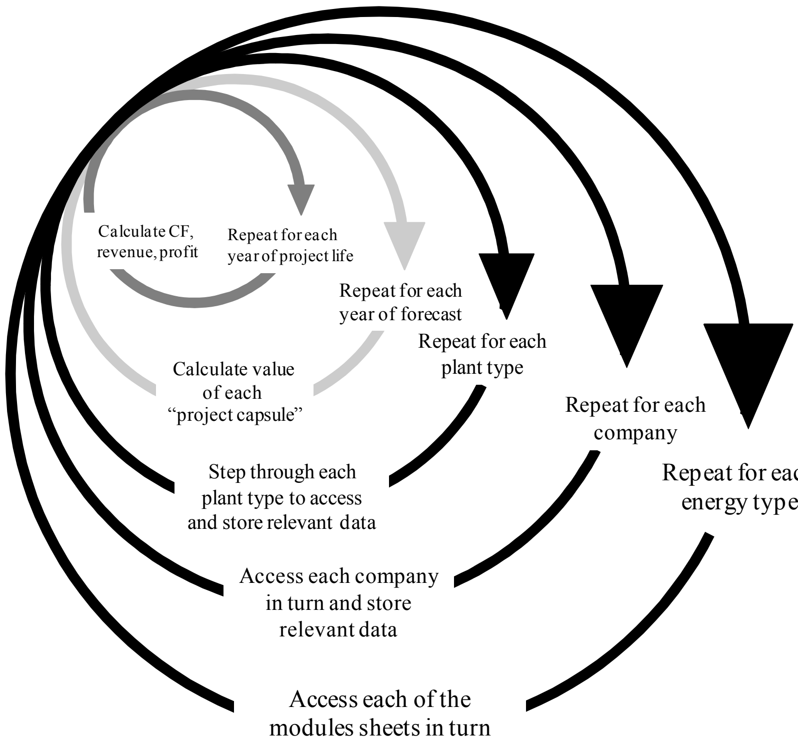



**Figure 3.11 Illustration of Principal Programming Cycles in Author's Model**

In addition, there are a number of variants of the program which allow certain aspects of additional analysis to be carried out, namely the sensitivity analysis and the Monte Carlo scenario analysis, requiring additional loops to be introduced into the program (see Section 3.5.3). In order to simplify the program, speed up the run time and enable the individual aspects of the results to be analysed in detail, these modules can be turned on and off by the user. The full list of loops appears in Table 3.3.

| Cycle | Description |
|---|---|
| **Energy Type Cycle:** | Moves through each energy type calculating possible capacity build-up in each case |
| **Company Cycle:** | Cycles through each of the companies being considered in turn |
| **Plant Type Cycle:** | Moves through each of the plant variants previously defined |
| **Launch Year Cycle:** | Examines projects begun in each of the analysis years under consideration |
| **Project Year Cycle:** | Calculates revenues, earnings and cash flows for each year in the lifetime of a project |
| **Sensitivity Analysis Cycle:** | Calculates sensitivity of results to a series of different input conditions |
| **Scenario Cycle:** | Considers results from each of four key scenarios |
| **Monte Carlo Cycle:** | Trials are carried out to simulate different conditions in each project year based around the means and standard deviations defined for each scenario in the Scenario Cycle |

**Table 3.3 Definition of Principal Programming Cycles in Author's Model**

Figure 3.12 presents a flow chart describing the "core engine" of the model. The term "core engine" is used to refer to the part of the program which generates the basic data about plant performance or to put it another way the "Project Capsules".

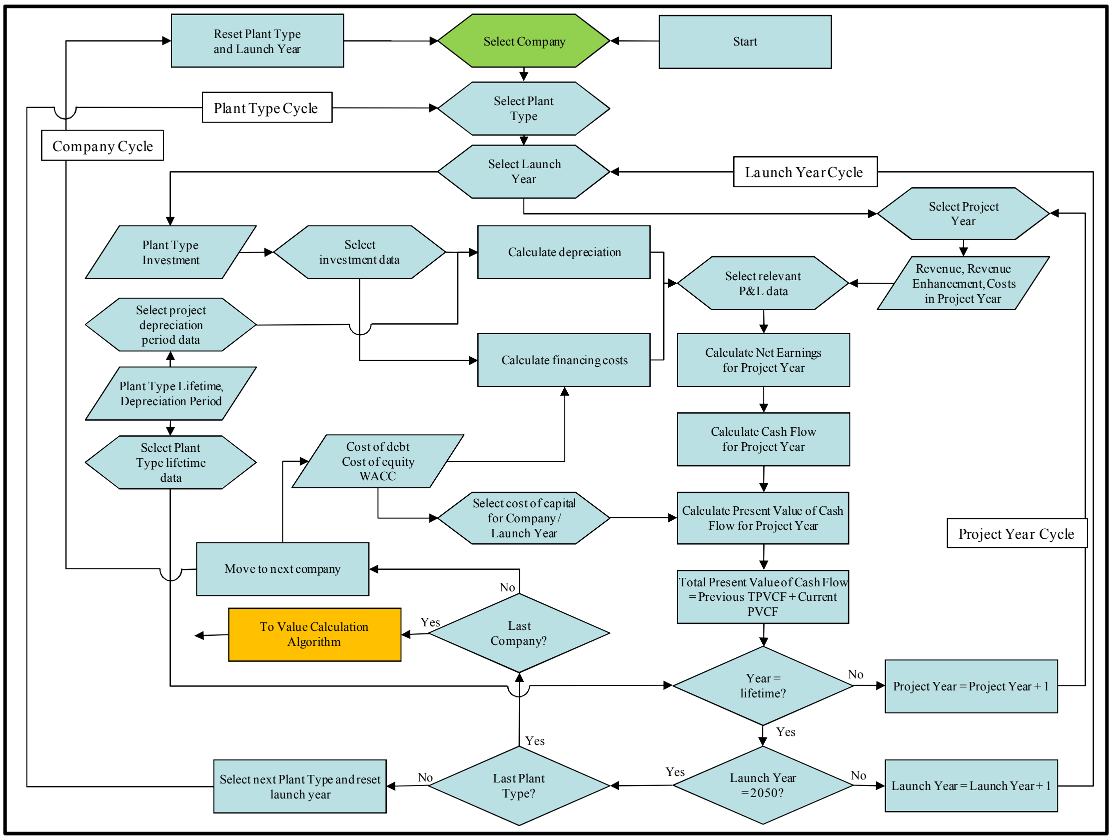



**Figure 3.12 Flow Diagram for Core Model Engine**

Four of the principal cycles described in Table 3.3 are included in the flow chart for the core engine and are clearly marked on the diagram. While the calculations of value contribution are integral to the way the model works the software has, in fact, been designed in such a way as to allow them to be made in a separate cycle. Thus, the core engine performs the basic project-related calculations and stores the data on expected revenues, profits, cash flows and so on, in an array which can subsequently be accessed for the purposes of making the company-specific value calculations. Separating the two functions has the benefit of allowing the core data to be maintained and for other value-related functionality to be bolted on in future, making the model more extensible. The flow chart pertaining to the value calculation algorithm is shown in Figure 3.13, which once again the cycles at work which are labelled as before.

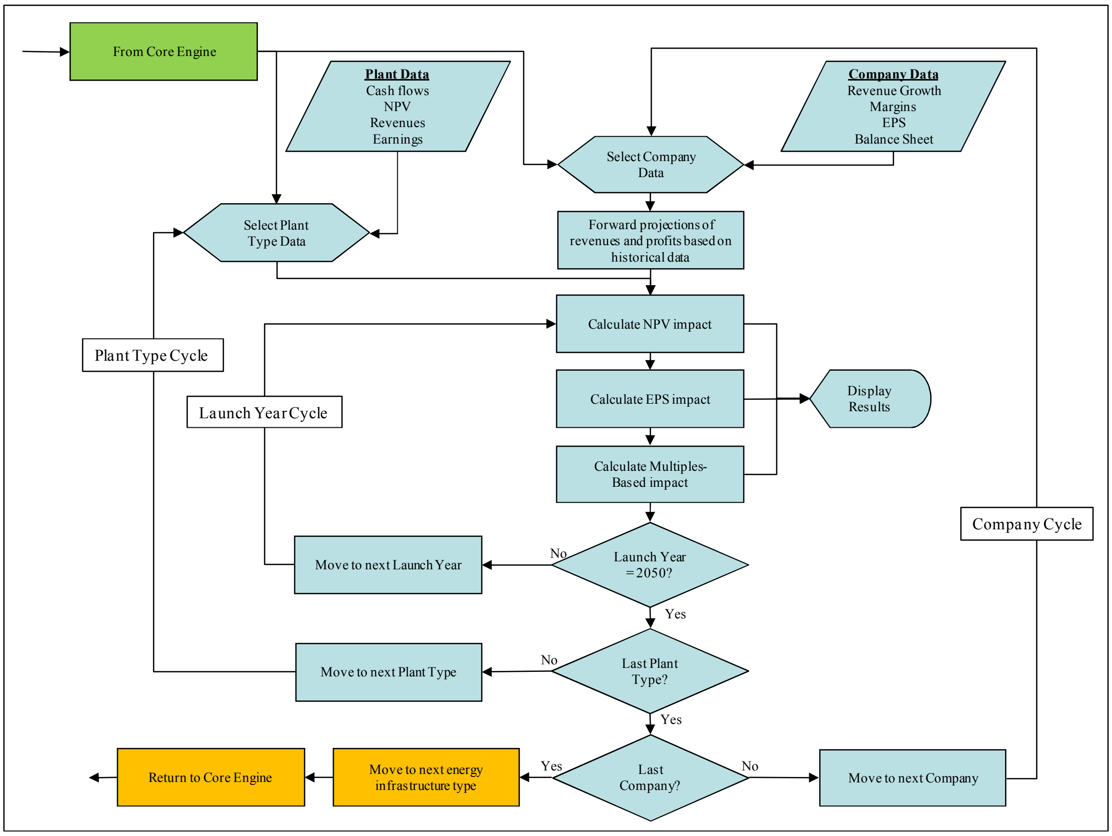



**Figure 3.13 Flow Diagram for Value Calculation Algorithm**

### 3.5.3 Modelling Uncertainty

Since the outcomes of models such as these are necessarily uncertain, two different approaches have been employed to investigate the impact of this uncertainty and these are described in more detail in the Sections 3.5.3.1 and 3.5.3.2. As was highlighted in Section 3.3 the timeframe modelled is the period 2010 – 2050 and the project capsules are in consequence modelled as far out as 2090. A level of uncertainty exists with respect to all the input parameters but it could be anticipated that this uncertainty would increase the further into the future the projections extend. What is more, consideration must be given to the fact that the outputs of the model derive from the combination of multiple uncertain input variables. A number of different techniques can be taken to represent uncertainty and, as mentioned, two of these are utilised in the current model.

#### 3.5.3.1 Probability weighted sensitivity analysis

Within the sensitivity analysis, a probability can be assigned to each of the possible input parameters being considered. Thus for a given parameter there may be one value which might be thought of as the mean or base case to which the highest probability might be assigned and then a series of other scenarios deviating progressively further from the mean to which increasingly lower probabilities would be applied. By way of example, the input parameter representing the price of petrol might be assigned values and probabilities according to the probability distribution function shown in Figure 3.14.

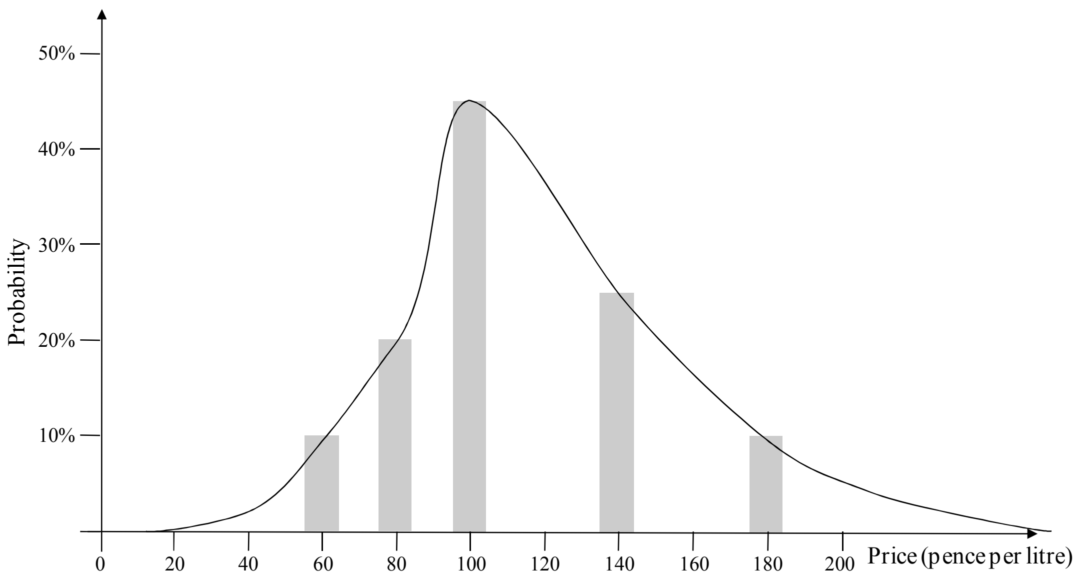



**Figure 3.14 Illustrative Probability Distribution Function for Transport Fuel Price**

This is roughly a normal distribution but skewed slightly towards the higher prices reflecting the user's expectation, in this instance, that prices would more likely be higher than the base case than lower. The probability-weighted output could then be calculated with reference to the values and probabilities of the inputs as shown in Table 3.4.

| Case | Price of Petrol (pence per litre) | Probability | Model Output, e.g. NPV (£m) |
|---|---|---|---|
| High-High | 180 | 10% | 12.0 |
| High | 140 | 25% | 10.0 |
| Base | 100 | 45% | 8.0 |
| Low | 80 | 20% | 7.0 |
| Low-Low | 60 | 10% | 6.0 |
| | **Probability Weighted Output** | | **9.3** |

**Table 3.4 Probability Weighted Analysis as Applied to Petrol Price in the Author's Model**

The benefit of doing this and calculating a single "most likely" output is to provide the user with a more easily understood result. Given the number of input variables having an impact on the model and the wide range of possible values being explored this can provide a useful complement to the range data.

#### 3.5.3.2 Monte Carlo analysis

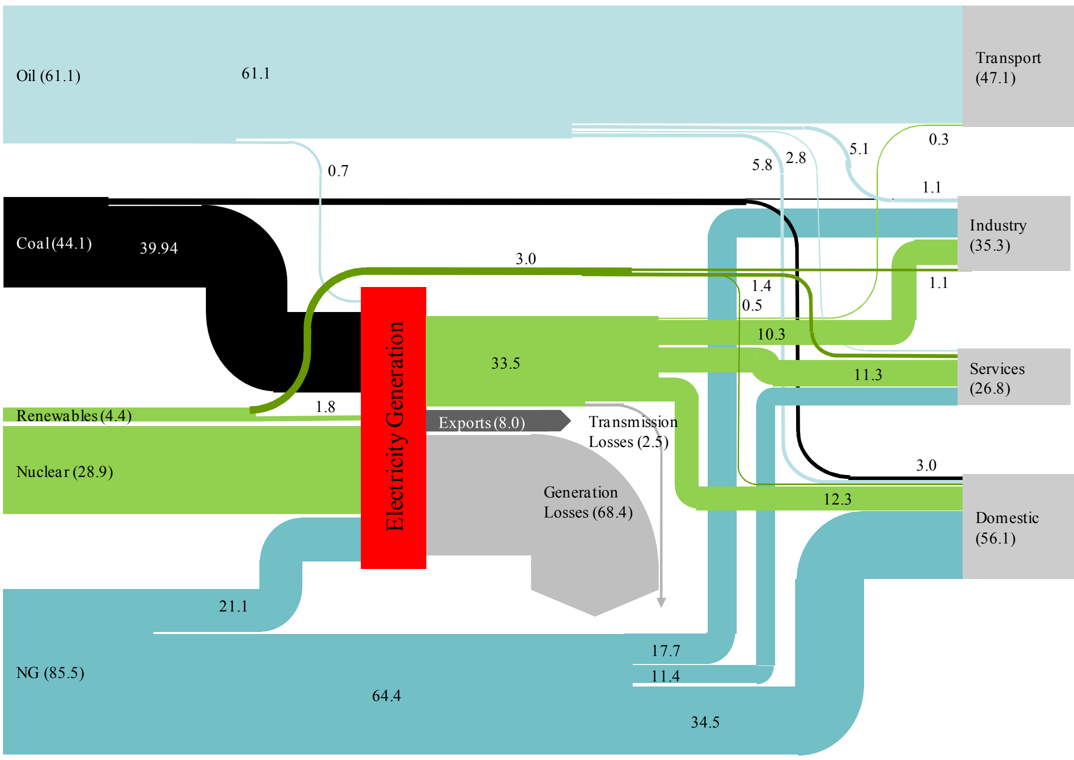
By contrast, in situations where there are a great many variables and the probabilities cannot be known with any degree of certainty it is frequently preferable to employ some form of Monte Carlo simulation. In this instance the Monte Carlo simulation is built around a normal distribution function using the iterative NORMINV function within Excel. The NORMINV (p, mu, sigma) function returns the value x such that, with probability p, a normal random variable with mean mu and standard deviation sigma takes on a value less than or equal to x. Thus, for each "trial" a random value is generated for each of the input parameters that is to be varied in the analysis based on a normal distribution for which the mean and standard deviation is defined by the user. The output value calculated for each trial is stored and the mean and standard deviation of the output parameters are in turn calculated (see Section 4.2.3 for a description of the means and standard deviations of the variables used in the Monte Carlo analysis).

## 3.6 *Application of the Model to the Scottish Context*

Having established the basic principles of the model and how it has been implemented in the Excel / VBA environment, this section details the specific data used in the Scottish application of the model.

### 3.6.1 Establishment of the Current and Future Demand Profiles

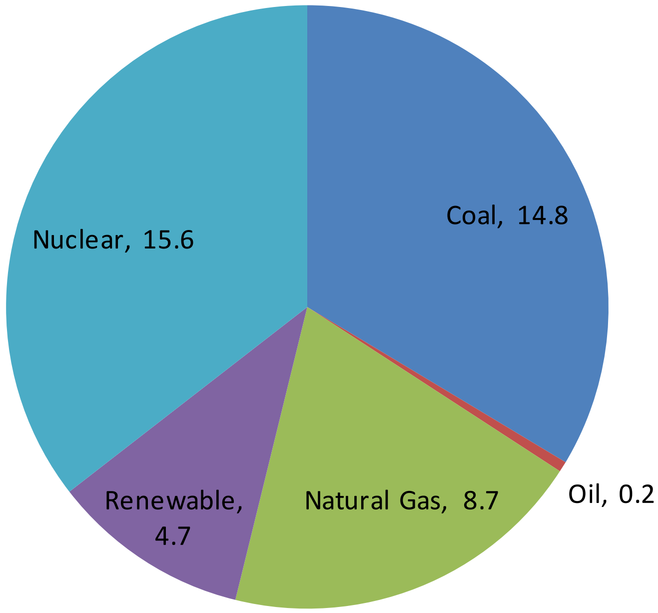
The initial demand is based on a set of data provided by the Scottish Government report in 2006 which provided an extensive survey of energy sources and uses in Scotland based on 2004 data [24]. The Sankey diagram in Figure 3.15 provides the overall view of energy sources and uses. The initial demand is broken down into four categories, Domestic, Industry, Services and Transport, while energy sources are split into five categories, namely Electricity, Gas, Oil, Solid and Renew / Heat.




*All figures in TWh*

**Figure 3.15 Energy Sources and Uses in Scotland (2004)**

The chart highlights the dominance of oil and gas in Scotland's final energy mix and that coal is still significant in terms of primary energy demand, although it is almost entirely directed towards electricity generation. Information regarding the split of electricity generation by fuel type is also important for developing future low carbon scenarios and this is presented in Figure 3.16.




*All figures in TWh*

**Figure 3.16 Breakdown of Electricity Consumption by Generation Type in Scotland (2004)**

Next an "Electricity and Hydrogen" scenario is proposed in which these two energy vectors based primarily on low-carbon electricity sources are the principal replacement for existing fossil fuels. The initial scenario is hydrogen and electricity centric on the basis that biofuels in Scotland face significant challenges while renewables are abundant compared with other regions. The conceptual design is shown in Figure 3.17.

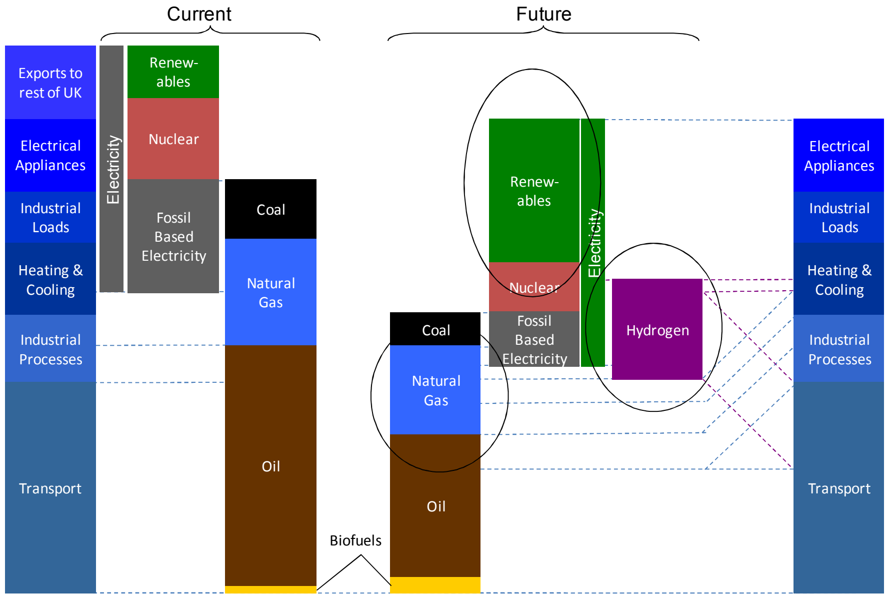



**Figure 3.17 Schematic Illustration of Current and Future Energy Sources and Uses in Scotland (not to scale)**

One further level of detail is required in order to begin the assessment of hydrogen's potential as a future energy vector and that is to understand the consumption figures by application type. This is important since there are certain applications where it is considered feasible to replace existing fuels with hydrogen and others where this appears less likely. For example, it is doubtful whether hydrogen could be used to power electrical appliances unless it was first converted to electricity and the model does not consider the use of hydrogen to produce electricity at a utility scale, hence this pathway is not considered. In fact it is envisaged that the new generation of hydrogen fuelled space heating would operate on a micro CHP basis but the electricity produced is not considered here nor has the use of portable fuel cells in mobile devices in order to simplify the analysis. On the other hand it is relatively easy to imagine hydrogen replacing natural gas for space heating so such a pathway is considered feasible. It is recognised that a value judgement is being made in so doing and that this might be considered inconsistent with the forecast but it is a necessary aspect of the model as constructed. The figures for application level consumption are not typically found in published data but an estimate of the figures has been arrived at using data from various sources [135]. The assumed load share figures by application are presented in Table 3.5.

| End User | Percent. Demand | | Energy Source | Percent. Demand | | Application Type | Percent. Demand |
|---|---|---|---|---|---|---|---|
| Domestic | 34.0% | ------> | Electricity | 21.9% | -----> | Appliances | 50.0% |
| | | | | | | Heat | 50.0% |
| | | | Gas | 61.5% | -----> | Heat | 100.0% |
| | | | Oil | 10.4% | -----> | Heat | 100.0% |
| | | | Solid | 5.4% | -----> | Heat | 100.0% |
| | | | Renew / Heat | 0.8% | -----> | Renew / Heat | 100.0% |
| Industry | 21.0% | -----> | Electricity | 29.3% | -----> | Industrial Process | 100.0% |
| | | | Gas | 49.5% | -----> | Industrial Process | 100.0% |
| | | | Oil | 14.9% | -----> | Industrial Process | 100.0% |
| | | | Solid | 3.0% | -----> | Industrial Process | 100.0% |
| | | | Renew / Heat | 3.3% | -----> | Industrial Process | 100.0% |
| Services | 16.0% | -----> | Electricity | 42.1% | ------> | Appliances, cooling | 70.0% |
| | | | | | | Heat | 30.0% |
| | | | Gas | 42.4% | ------> | Heat | 100.0% |
| | | | Oil | 10.4% | ------> | Heat | 100.0% |
| | | | Solid | 0.1% | ------> | Heat | 100.0% |
| | | | Renew / Heat | 5.0% | ------> | Heat | 100.0% |
| Transport | 29.0% | ------> | Oil | 99.4% | ------> | Road | 71.0% |
| | | | | | | Rail | 4.0% |
| | | | | | | Marine | 7.0% |
| | | | | | | Aviation | 18.0% |
| | | | Electricity | 0.6% | ------> | Rail | 100.0% |

**Table 3.5 Share of Energy Demand Broken Down by Application Type in Scotland (2004)**

Note that the relative proportion of demand attributable to each main category (the left hand column in Table 3.5) of demand is not expected to change, e.g. there is no significant move by domestic consumers to shift from road to rail. Based on the analysis of current consumption by application a forward projection of the same is made for 2050, based around the principal scenario which can be summarised as follows:

- Almost complete elimination of coal from the mix until much later when Carbon Capture and Storage (CCS) becomes feasible;
- Significant reduction in the use of oil and gas but not total elimination;
- Modest contribution from biofuels; and
- Low carbon electricity and hydrogen are the mainstay of energy delivery

| Application | Energy | 2010 | 2050 | Commentary |
|---|---|---|---|---|
| Appliances | Electricity | 100% | 100% | The supply of energy to appliances remains supplied from electricity generation and the model does not consider the use of hydrogen to produce electricity at a utility scale. In fact it is envisaged that the new generation of hydrogen fuelled space heating would operate on a micro CHP basis but the electricity produced is not considered here nor has the use of portable fuel cells in mobile devices in order to simplify the analysis. |
| Heat | Electricity | 14% | 45% | The penetration of electricity for the provision of heating is relatively high in Scotland when compared with the rest of the UK. It is anticipated in the base case scenario that electric heating would grow to significantly replace existing gas fired heating. |
| | Hydrogen | 0% | 25% | Hydrogen is seen as having the potential to replace part of the heating energy currently satisfied with natural gas. It is considered that this would only be feasible within a subset of the building stock and is, therefore, capped at 25%. |
| | Renew / Heat | 2% | 10% | It is anticipated that there would be a significant increase in the use of waste heat and other renewable heating technologies such as solar thermal. Thus the proportion of heating energy attributable to these means rises to 10%. |
| | Biofuels | 0% | 10% | Similar to renewable / waste heat sources it is anticipated that there would be a significant increase in the use of bio gas rising from zero today to 10%. |
| | Gas | 67% | 10% | Dependence on natural gas, the primary source of heating fuel today, is significantly reduced |
| | Oil | 13% | 0% | Like electricity, oil satisfies a more significant component of heating demand in Scotland reflecting the lower penetration of natural gas. This is expected to be completely phased out over the period of the study. |
| | Solid | 4% | 0% | The use of coal for heating is once again this is expected to reduce to zero over the period of the study. |
| Industrial Processes | Electricity | 29% | 35% | A modest increase in the use of electricity for industrial processes is anticipated. |
| | Renew / Heat | 3% | 13% | A significant increase in the use of renewable systems is expected as the technologies reach maturity |
| | Natural Gas | 50% | 40% | A relatively modest decrease in the use of natural gas is expected. This is based on the concept that certain processes might not lend themselves to easy conversion to other energy sources. |
| | Oil | 15% | 10% | Similarly, oil shows a modest decrease in light of potential issues with switching to alternatives. |
| | Solid | 3% | 2% | Coal represents a very modest proportion of industrial demand and is anticipated to decrease slightly. |

**Table 3.6a Current and Forecast Proportional Contribution in 2050 to Total Energy Demand by Energy Type and Application**

| Application | Energy | 2009 | 2050 | Commentary |
|---|---|---|---|---|
| Road Transport | Electricity | 0% | 20% | While hydrogen is taken to dominate road transport in the base case future scenario, electric vehicles are expected to show a significant penetration over the period rising to 20% of the overall demand. Note that FCVs strictly speaking form part of the set of electric vehicles but here BEVs and plug-in hybrids could be considered to form part of the mix. |
| | Hydrogen | 0% | 70% | Hydrogen is taken to dominate in the base case scenario meeting 70% of transport demand. |
| | Biofuels | 0% | 5% | Biofuels remain capped at a relatively low 5% reflecting the emphasis in the base case on a hydrogen plus electricity "story". |
| | Oil | 100% | 5% | Oil is virtually eliminated from the picture with the residual reflecting the presence of a remnant fleet of vehicles. |
| Rail Transport | Electricity | 14% | 75% | Penetration of electrification is relatively lower in Scotland (23% of routes) than the UK as a whole (38%). In line with Scottish Government Strategic Transport Plan, an increase to 75% of all passenger journeys is expected. |
| | Hydrogen | 0% | 15% | In line with the increase in the use of hydrogen in the road transport network it is anticipated that the infrastructure could be leveraged especially in the remoter routes where electrification is not cost effective. |
| | Biofuels | 0% | 5% | Biofuels are expected to represent the same proportion of overall demand as for road transport. |
| | Oil | 86% | 5% | In line with the overall strategy of eliminating oil from transport demand, this reduces to 5%. |
| Marine Transport | Hydrogen | 0% | 20% | It is anticipated that hydrogen could play a modest role in marine transport, once again leveraging the wider infrastructure. |
| | Biofuels | 0% | 5% | Biofuels represent a consistent 5% |
| | Oil | 100% | 75% | It is anticipated that the impetus for technological development towards alternative fuels in the marine sector might be lower given the greater challenges and the longevity of marine fleets. Thus oil remains a significant part of overall demand. |
| Aviation | Hydrogen | 0% | 2% | Hydrogen is not anticipated to make a significant contribution to aviation demand. |
| | Biofuels | 0% | 3% | Similarly, biofuels are not expected to show great penetration and at a lower level than elsewhere in the energy value chain. |
| | Oil | 100% | 95% | Oil continues to dominate demand reflecting the particular constraints in aviation. |

**Table 3.6b Current and Forecast Proportional Contribution in 2050 to Total Energy Demand by Energy Type and Application**

Projecting forward to 2050, overall demand is calculated with reference to the growth in demand suggested by Scottish Government figures [24]. The basic growth figures represent the demand assuming that the efficiency of applications remains constant and must be modified to take account of the improved application efficiencies associated with significant shifts in technology such as a move to fuel cell vehicles. The projected scenario is presented in Tables 3.6a and 3.6b. It is important to recognise that this represents one potential end point which allows a pathway to that end point to be defined. Since the model takes an iterative approach this does not preclude alternative outcomes but it is worth reflecting on the extent to which the end point chosen would influence the behaviour of the model and this is discussed in Chapters 0 and 5 which present the results of the analyses. Table 3.7 provides the demand in TWh by energy source / vector at equivalent efficiencies, that is to say assuming no change to the efficiencies of applications. However, application efficiencies are indeed expected to improve and demand is then calculated and modified to reflect these efficiency improvements at point of use. For example, a 100% improvement is applied where electricity or hydrogen replaces fossil fuels in transport (i.e. demand halved), reflecting the doubling of energy conversion efficiency expected with the use of fuel cells.

| | Current | | Target | | | |
|---|---|---|---|---|---|---|
| | Percent. | In TWh | Percent. | In TWh at Equivalent Efficiency | In TWh at Improved Efficiencies | Percent. |
| Hydrogen | 0.0% | - | 25.4% | 53.37 | 26.69[a] | 15.0% |
| Electricity | 20.5% | 35.12 | 39.6% | 83.12 | 77.77[b] | 43.7% |
| Gas | 38.1% | 65.19 | 12.6% | 26.36 | 26.36[c] | 14.8% |
| Oil | 37.1% | 63.57 | 9.6% | 20.22 | 20.22[d] | 11.4% |
| Solid | 2.5% | 4.25 | 0.4% | 0.88 | 0.88[e] | 0.5% |
| Renew / Heat | 1.8% | 3.02 | 6.9% | 14.46 | 14.46[f] | 8.1% |
| Bio-fuels | 0.0% | - | 5.5% | 11.55 | 11.55[g] | 6.5% |
| | 100.0% | 171.14 | 100.0% | 209.97 | 177.94 | 100.0% |

*Notes:*

*a Based on 2x tank to wheels efficiency improvement for vehicles*

*b Based on a 1.5x tank to wheels efficiency for electric vehicles*

*c Minimal efficiency improvements envisaged*

*d No efficiency improvement included in base case. Govt target to reduce average vehicle emissions to 130g / km is noted however.*

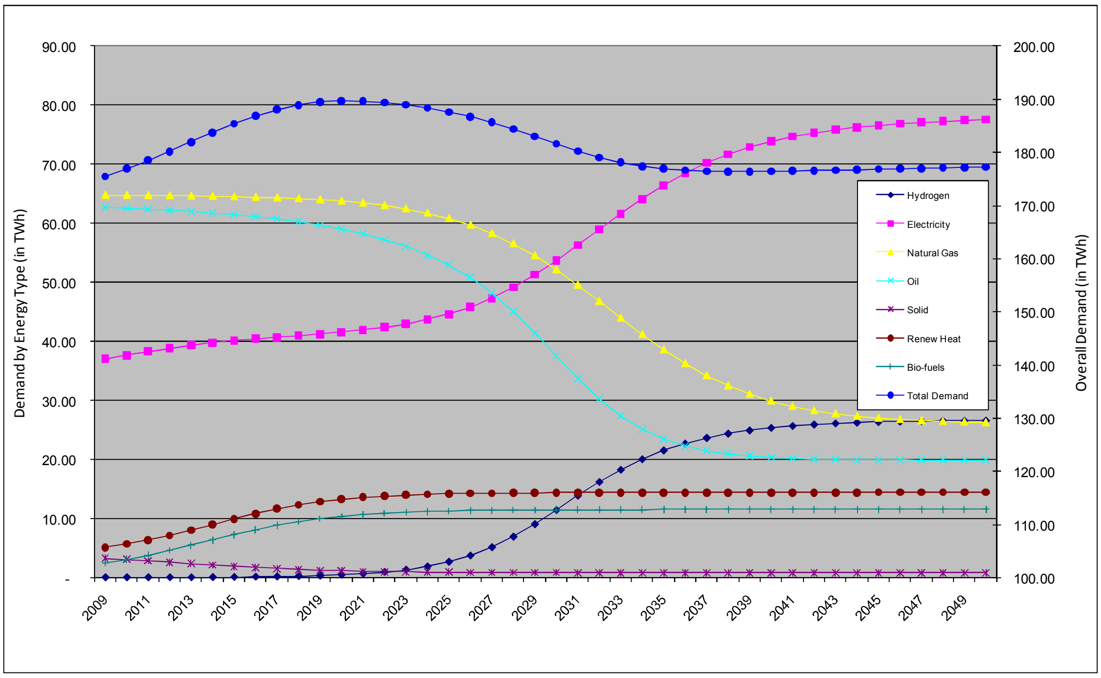
*e Minimal efficiency improvements envisaged*

*f Minimal efficiency improvements envisaged*

*g Minimal efficiency improvements envisaged (but note point under d)*

**Table 3.7 Proportional Current and Forecast Final Demand In 2050 by Energy Type, Excluding and Including Application Efficiency Improvements**

Having arrived at a target demand by application and energy type for 2050, the next step is to fill in the intervening years according to a logistic function or s-curve. The parameters of the s-curve reflect the author's own expectations of a "reasonable" speed of uptake which is in turn based upon information from key sources including World Wind Energy Association (WWEA) data on the growth of installed wind capacity worldwide [136]. Since these s-curves are developed independently from one another, when viewed in conjunction, they could offer an "unrealistic" picture of demand growth during the intervening years even if it is considered that the "end" picture in 2050 is realistic. In order to compensate for this eventuality a feedback loop exists which prevents the overall demand growth exceeding a user-specified figure. The evolution of demand over time is indicated in Figure 3.18.



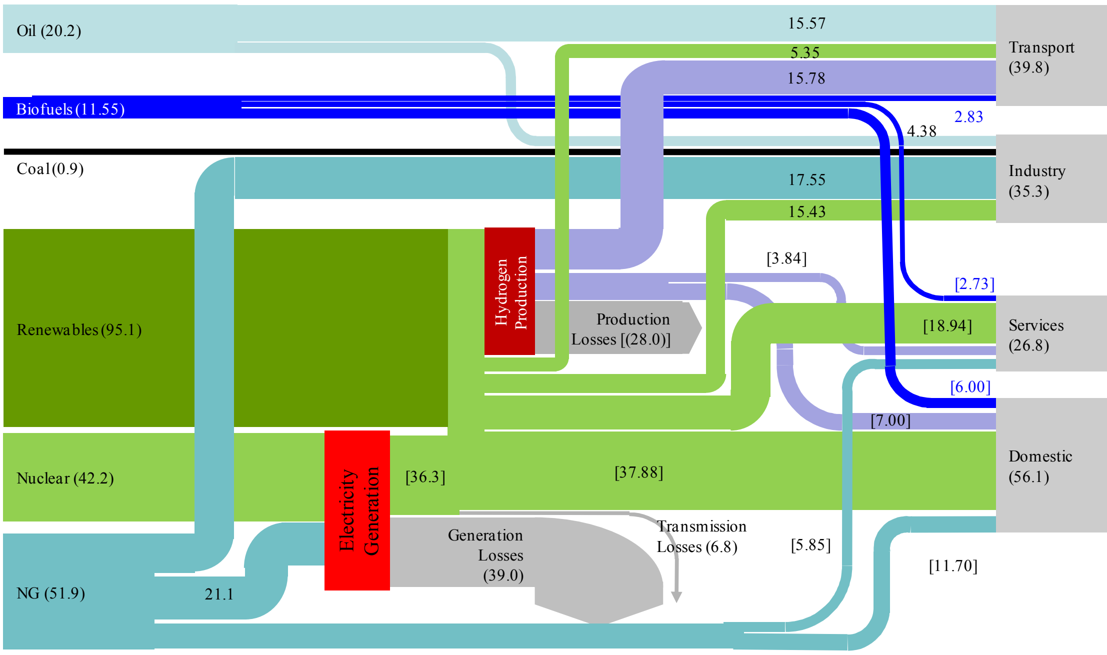

*Note: Capacity factors are introduced here and so when the adoption curves are used to calculate the capacity to meet demand this has already been factored in. Thus, when calculating the number of units of each type of plant there is no need to apply the CF a second time.*

**Figure 3.18 Forecast Demand by Energy Type 2010 – 2050**

Finally, having established the end-user demand scenario, the primary demand forecast can also be established bearing in mind the need to consider:

- Natural gas required for electricity production;
- Natural gas required for hydrogen production; and
- Electricity for hydrogen production.

The split of primary consumption by energy source / vector in the final year developed on the basis of this data and analysis is shown in Figure 3.19.




*All figures in TWh*

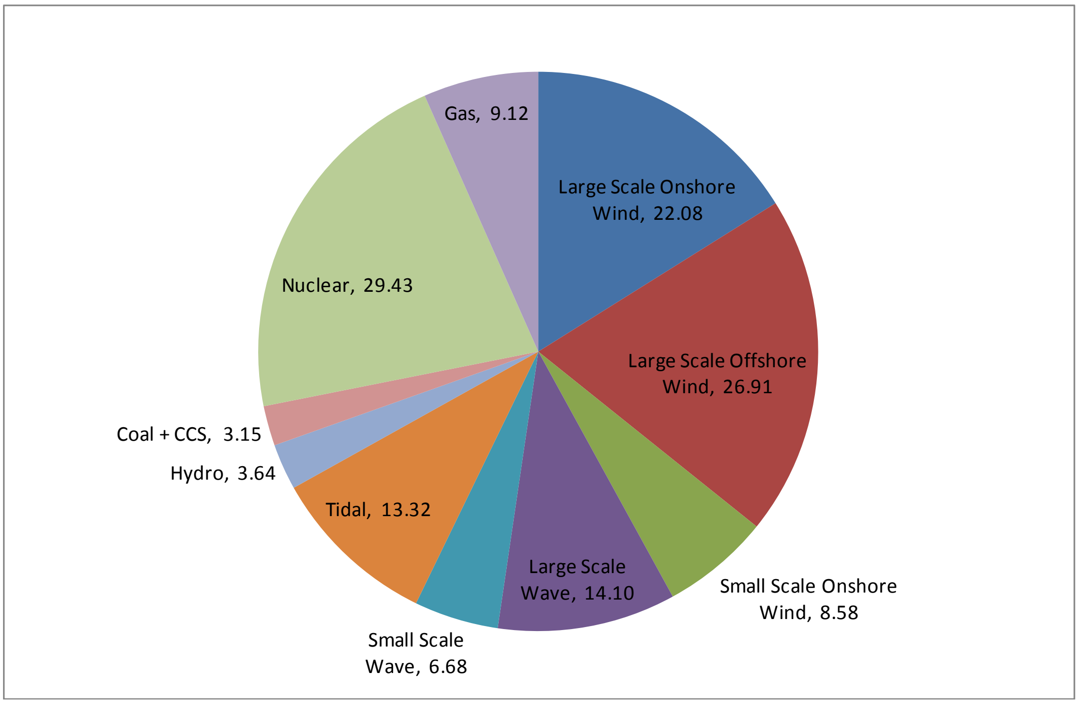
**Figure 3.19 Forecast Energy Sources and Uses in Scotland (2050)**

The future generation mix is arrived at based on certain assumptions about the likely future penetration of different generation types. This projection is made with reference is always made to the potential capacity available as shown in Table 3.8.

| Technology | Potential Capacity [137] | | Assumed Capacity in Model (TWh) |
|---|---|---|---|
| | Capacity (GW) | Energy (TWh) | |
| Onshore wind | 11.5 | 45.0 | 22.1 |
| Offshore wind | 25.0 | 82.0 | 26.9 |
| Wave | 14.0 | 45.7 | 20.8 |
| Tidal stream | 7.5 | 33.5 | 13.3 |

**Table 3.8 Potential Renewable Capacity in Scotland**

The assumed split across all generation types including fossil and nuclear plant in 2050 is provided in Figure 3.20.




*All figures in TWh*

**Figure 3.20 Forecast Future Electricity Generation Mix in Scotland (2050)**

### 3.6.2 Establishment of the Supply Function

The basic premise underpinning the initial supply forecast is that supply will follow demand and that supply capacity will increase to meet the required level of demand at a given point in time. Needless to say, this is, at some level, an ideal view but over the timeframe of the analysis it is likely to be a good approximation assuming the opportunity exists for companies to invest in value enhancing projects. The model includes a defined number of plant variants the characteristics of which can be altered by the user if desired. These are brought into the mix according to certain rules which again may be defined by the user and which are dependent on certain logical assessments as to their applicability to certain end user applications. The plant variants and capacity expansion rules are described in the following sections of this Thesis. It is critical to recognise that these rules are only used to elaborate the initial scenario and do not define the "investment decisions" ultimately made in the model by companies operating in the different markets. These decisions will be dependent on the investment decision criteria described in Section 3.4 which will ultimately determine whether or not the anticipated plant roll-out is achieved or not. The raises the question of whether the starting point *ex ante* affects the outcome, as previously mentioned in Section 3.6.1, and this is undoubtedly the case. However, without making some assumptions at the outset regarding supply or demand the problem would otherwise be immutable. Thus it is considered reasonable to anticipate a certain level of demand and a potential set of supply infrastructure and to determine whether or not the investment rules defined in the model would lead suppliers to build out capacity to meet that demand. If not, the demand scenario can be reviewed accordingly.

#### 3.6.2.1 Hydrogen

Hydrogen demand has been defined in Section 3.6.1 to consist of two elements, namely transportation and heating which are treated in slightly different ways in the analysis. In order to arrive at an initial model of supply infrastructure it is first necessary to define the type of plant in which companies would have the opportunity to invest. In the model it is assumed that all the hydrogen demand is supplied from three types of plant each with at least four possible variants as shown in Table 3.9. The relative proportion of demand supplied by each of the variants can be set independently by the user and a number of different regimes have been explored by the author that are described more fully in Chapter 5.

*a) Small and Large Refuelling Stations*

These plant are destined to satisfy the needs of the transport sector and hence the number of refuelling stations required to meet the desired capacity is defined by three factors:

1. Transport fuel demand as defined in Tables 3.6a and 3.6b;
2. Refuelling station capacity as defined in Table 3.9; and
3. The desired split between different plant defined by the user

The model rounds to the nearest integer number of plant and thus the capacity supplied by these stations may slightly lag or slightly lead demand. Four out of the six refuelling station plant categories are envisaged to have onsite production of hydrogen while the other two are supplied with hydrogen from outside and the relative proportion of these may be varied at will. For the sake of simplicity, one size of plant is chosen supplying all applications: private cars; public transport; commercial vehicles. Refuelling stations only start to be built once the capacity required to meet demand exceeds 50% of the capacity of a single unit with transport demand assumed to be met ad-hoc from hydrogen produced at Small Scale Multi Purpose Plants (as defined below) before this time. The model allows for an initial proportion and a final proportion of different plant types to be defined (this may remain the same, increase or decrease) and the default position is set so that initially 100% of units are of standalone type with this reducing to 75% over 25 years. The period over which this change in proportion occurs can also be defined at will and it is assumed to change on a straight line basis.

In a similar vein, the split between Steam Methane Reforming Units and Electrolysis Units may be defined and varied over a defined time period. Finally, the split between units producing compressed gas or liquid hydrogen may also be defined in the same way. Once the number of each type of unit has been defined, the model goes on to calculate how many new and replacement plants would need to be built annually. The number of new plants to be built is simply defined by the cumulative number of plants in year x, less the cumulative number of plants in the preceding year (x – 1), subject to the condition that the number of plants is increasing (otherwise the number of new plants is zero). In each year the number of plants ready for replacement is calculated according to the defined lifetime of the plant. It is recognised that in any given year some plant may need to be retired as the number of that type of plant may be declining (depending on the parameters previously defined) and this is defined simply by the difference between the number of plant in year (x – 1) and year x, subject to the condition that the number of plant is decreasing. Thus the number of plant replaced is the number of plants requiring replacement less the number of retirements. The transport demand not satisfied by the filling stations – either before filling stations start to be built or where there is a shortfall in capacity – is met ad hoc by the Multi-Purpose Units (Small or Large Scale) and these units also meet the demand from those filling stations requiring external supply. Supply from these Multi-Purpose Units is made either via a network of pipelines or, more likely, a tanker delivery network and this is discussed in more detail in paragraphs 3.6.2.1 (d) and (e) below.

*b) Micro and Small Scale Multi-Purpose Units*

Being the most flexible and smallest sized units these provide fill-in capacity and satisfy all early demand before standalone filling stations and large scale units start to be built. However, the dynamic system is led by the building of Large Scale Units emphasising the fill-in nature of these small units. The number of units is determined by subtracting the installed capacity from the total demand, dividing by the unit size and rounding to the nearest integer. Retirements and replacements are calculated in the same way as described above. The other dynamics of the system are described in Paragraph (c) which discusses the introduction of the large scale units.

c) *Mid and Large Scale Multi-Purpose Units*

The introduction of multi-purpose units functions as follows:

1. Demand for heating energy plus that required by externally supplied refuelling stations is defined, as discussed in Section 3.6.1.
2. The relative proportion of demand that is to be met by Large Scale units is defined by the user depending on the type of regime that is to be explored together with the split of unit variant.
3. The number of Large Scale units is calculated by dividing the demand by the unit capacity rounded to the nearest integer.
4. Small Scale Units then make up the additional un-met demand.

Units are replaced / retired in the same way as described previously.

*d) Pipeline Delivery Infrastructure*

The model has the option for a proportion of piped hydrogen for heating to be shipped as a mixture of hydrogen and natural gas and rest to be shipped in dedicated pipelines. The proportion of the total demand that can be shipped as a mix as well as the maximum volumetric content can be set by the user with the combined default proportion being 30%. The maximum allowable amount of hydrogen is carried as a mix, with the actual amount carried being limited either by the allowable volumetric content or the demand for hydrogen whichever is lower.

A full analysis of the impact of modifications to the existing pipeline network or the creation of a new network would require knowledge of the implantation of all the points of production and demand and such an undertaking is considered beyond the scope of the current research. Consequently, a simplification is introduced whereby it is assumed that for every million cubic metres of hydrogen carried as a mix annually, 2km of natural gas infrastructure would require modification.

| Type | Capacity (kg of $H_2$ / day) | Variants | Capital Cost in 2010 (£m / unit) |
|---|---|---|---|
| **Small and Large Refuelling Stations** – Used to deliver transport fuel to domestic and commercial vehicles in a similar way to existing roadside refuelling infrastructure. Capacity reflects the average capacity of existing petrol / diesel stations, recognising the superior efficiency of hydrogen fuelled vehicles, i.e. delivery capacity is roughly half that of existing petrol stations. | 1,000 / 2,000 | Natural gas, onsite steam methane reformation, compressed $H_2$ output (RNGC) | 4.0 - 5.0 |
| | | Natural gas, onsite steam methane reformation, liquid $H_2$ output (RNGL) | 4.0 - 5.0 |
| | | Onsite electrolysis, compressed $H_2$ output (REC) | 4.0 - 5.0 |
| | | Onsite electrolysis, liquid $H_2$ output (REL) | 4.0 - 5.0 |
| | | Compressed $H_2$ refuelling station supplied externally (RC) | 2.5 - 3.0 |
| | | Liquid $H_2$ refuelling station supplied externally (RL) | 2.5 - 3.0 |
| **Micro and Small Scale Multi-Purpose** – Production units used to deliver hydrogen fuel for a variety of applications. This could include supplying fuel into a heating or transport fuel network or providing fuel for a specific location, e.g. a modest building or a small transport fleet. | 300 / 1,500 | Natural gas, onsite steam methane reformation, compressed $H_2$ output (SMNGC) | 1.5 - 2.5 |
| | | Natural gas, onsite steam methane reformation, liquid $H_2$ output (SMNGL) | 1.5 - 2.5 |
| | | Onsite electrolysis, compressed $H_2$ output (SMEC) | 1.5 - 2.5 |
| | | Onsite electrolysis, liquid $H_2$ output (SMEL) | 1.5 - 2.5 |
| **Mid and Large Scale Multi-Purpose** – Production units used to deliver hydrogen fuel for a variety of applications. This could include supplying fuel into a heating or transport fuel network or providing fuel for a specific location, e.g. a large building or a large transport fleet. | 35,000 / 300,000 | Natural gas, onsite steam methane reformation, compressed $H_2$ output (LMNGC) | 50.0 – 150.0 |
| | | Natural gas, onsite steam methane reformation, liquid $H_2$ output (LMNGL) | 50.0 – 150.0 |
| | | Onsite electrolysis, compressed $H_2$ output (LMEC) | 50.0 – 150.0 |
| | | Onsite electrolysis, liquid $H_2$ output (LMEL) | 50.0 – 150.0 |

*Source: Cost data based on information from the DOE targets for hydrogen delivery [57] and from Shell Hydrogen [138]*

**Table 3.9 Description of Hydrogen Production Plant Variants**

The remaining hydrogen for heating, shipped in dedicated pipelines, is assumed to require an additional 2km of new pipeline infrastructure to be built for every million cubic metres of hydrogen transported. The figures are arrived at based on the current total volume of natural gas delivered (143 billion $m^3$ [139]) per unit length of gas distribution network (275,000km [140]). Note that this is based around the relative density at Standard Temperature and Pressure (STP) of $H_2$ and Natural Gas.

*e) Tanker Delivery Infrastructure*

The number of tanker units required is defined based on the number of refuelling stations requiring an external supply, the size of the tanker units and the number of deliveries each unit can make per day. The size of the unit is definable by the user with the default position being set at a capacity of 2,000kg of liquid hydrogen and units are assumed to be able to make on average 1.5 deliveries per day. This is based upon current petrol tanker sizes [141] and the author's own assumption regarding the number of delivery visits that a tanker can make in a single day. Essentially, the assumption is that a tanker can make at least one delivery per day but is unlikely to be able to average greater than two on average across the whole of Scotland.

#### 3.6.2.2 Electricity

In much the same way as for hydrogen infrastructure, the electricity model is built around the overall demand and a set of plant variants and certain assumptions about the penetration of each of those variants. Renewables plant characteristics are defined in Table 3.10.

| Type | Unit Capacity (MW) | Capacity Factor[a] | Final Installed Capacity (GW) | Cost in 2010 (£m per MW)[b] |
|---|---|---|---|---|
| Large Onshore Wind | 300 | 0.28 | 9.0 | 0.81 |
| Large Offshore Wind | 600 | 0.32 | 9.6 | 1.30 |
| Small Onshore Wind | 50 | 0.28 | 3.5 | 0.48 |
| Large Wave | 300 | 0.35 | 6.9 | 1.60 |
| Small Wave | 30 | 0.30 | 3.8 | 1.70 |
| Tidal | 200 | 0.40 | 3.8 | 1.50 |
| Coal + CCS | 200 | 0.60 | 0.4 | 2.00 |

*Sources:*

a. *DUKES www.decc.gov.uk*

b. *Wind plant estimates based on various sources including ScottishPower, announced costs for recent wind projects, BWEA data. Wave and tidal costs representative of medium term expectations from Carbon Trust Future Marine Energy [142], author's own estimates*

**Table 3.10 Description of Proposed Renewable Generation Plant Types in Scotland**

The build up of each renewable plant type follows a defined s-curves. Replacements are dealt with in the same way as for hydrogen plant. Existing electricity generation plant is dealt with differently since here the decision-making process is driven by whether or not to replace plant rather than to build new plant. Table 3.11 provides details of the plant to be replaced or phased out while Appendix 7.2 provides details of all existing renewable and conventional plant in Scotland.

| Type | | Capacity (MW) | Capacity Factor[a] | Comments | Cost in 2010 (£m per MW)[b] |
|---|---|---|---|---|---|
| Gas-Fired Plant | CCGT | 1,300 | 0.43 | Assumed that the one CCGT is replaced in 2025 | 0.58 |
| | CHP | 120 | 0.43 | Assumed that the one large CHP plant is replaced in 2025 | 0.83 |
| Coal-Fired Plant | | 1,500 – 2,000 | 0.43 | Gradually phased out with both existing plants being completely shut in 2018. It is not assumed in the base case of the model that any coal + CCS plant would be built | NA |
| Nuclear | | 2,400 | 0.75 | Two existing plants are replaced in 2015 and 2020 respectively | 0.63 |
| Diesel Plant | | 20 | 0.75 | Plant phased out in 2020 | NA |
| Hydro | | 20 | 0.32 | Plant totalling 20MW replaced in 2015, 2025, 2035 and 2045 | 2.50 |

*Sources:*
*a. DUKES www.decc.gov.uk*
*b. Based on announced plant costs*

**Table 3.11 Current and Forecast 2050 Conventional Plant Capacities in Scotland**

In line with the significant increase in renewable capacity it is envisaged that the transmission system could require significant new investment as well. This is mitigated in part by the application of some of the renewable capacity to the production of hydrogen. However, much of the capacity will require connection to the grid and will be located in regions where no grid currently exists or where it is weak. Both AC and DC grid new build and strengthening will be required to meet the demand and is added in the model on the basis shown in Table 3.12. In much the same way as for the gas network, the model assumes that the build out of new grid is proportional to the additional capacity of different type of plant that is installed. Once again this ignores the spatial aspects of the exact siting of new plant and in effect assumes an average distance to new plant from the existing network. The current transmission network is the UK is roughly 25,000km in length [143], suggesting a ratio of 70 km / TWh of transmission capacity.

| Type of Capacity | New AC Grid (km / TWh of additional capacity) | Cost in 2010 (£m per km) | New DC Grid (km / TWh of additional capacity) | Cost in 2010 (£m per km) | Strengthening (km / TWh of additional capacity) | Cost in 2010 (£m per km) |
|---|---|---|---|---|---|---|
| Large Onshore Wind | 25 | | 0 | | 50 | |
| Large Offshore Wind | 10 | | 25 | | 25 | |
| Small Onshore Wind | 10 | 0.82 | 0 | 1.15 | 10 | 0.10 |
| Large Wave | 10 | | 25 | | 25 | |
| Small Wave | 0 | | 10 | | 10 | |
| Tidal | 10 | | 25 | | 25 | |
| Coal + CCS | 25 | | 0 | | 10 | |

**Table 3.12 Build-Out of Transmission Capacity Required by Expansion in Capacity of Different Renewable Generation Type**

There are two aspects to the required increase in transmission capacity; first, an increase in overall generation capacity and, second, a change in its physical location with the shift to more renewables. Since a proportion of electricity demand goes towards centralised production of hydrogen only a proportion of new generation capacity is considered to require new grid or grid strengthening. This additional grid capacity is split equally between new grid and grid strengthening and between AC and DC capacity according to whether it is onshore or offshore as shown in Table 3.21. Replacement of plant is dealt with in the usual way.

### 3.6.2.3 Natural Gas

No new or replacement plant is accounted for except as discussed in Section 3.6.2.1 (e) since it is not considered that additional storage or handling facilities would be required as the amount of natural gas consumed is set to decrease. Provision is made for the replacement of 1 million m$^3$ of storage capacity every 10 years reflecting the roughly 60 million m$^3$ of UK storage that could be attributed to Scotland (excluding the Rough subsea facility).

#### 3.6.2.4 Oil

One refinery replacement is anticipated in 2025 but no new refining capacity is envisaged.

#### 3.6.2.5 Coal

No additional plant is anticipated.

#### 3.6.2.6 Renewable Heat

It is assumed that the contribution made by renewable heat sources falls into two distinct categories, waste heat plant and solar thermal plant which are characterised in Table 3.13.

| **Plant Type** | **Unit Size (MW)** | **Capacity Factor** | **Cost in 2010 (£m per MW)** |
|---|---|---|---|
| Waste Heat Plant | 5.0 [a] | 0.6 [c] | 0.39 [e] |
| Solar Thermal | 0.5 [b] | 0.15 [d] | 0.34 [d] |

*Sources:*
a. *Comparable to small CHP gas turbine plant*
b. *Requirement for 100 – 200 home community*
c. *Based on typical capacity factor for feeder energy plant*
d. *Based on data from http://www.sandia.gov/Renewable_Energy/solarthermal/NSTTF/feature.htm*

**Table 3.13 Definition of Renewable Heat Plant Types**

The number of plant retirements / replacements is calculated as previously.

#### 3.6.2.7 Biofuels

In terms of biofuels, once again two categories are considered, biogas plants using waste or other biomass primarily for heating and biofuel refineries for the production of transport fuel. These plant are defined in Table 3.14.

| Plant Type | Unit Size[a] | Capacity Factor[b] | Cost in 2010 (£m per unit of output)[c] |
|---|---|---|---|
| Biogas Plant | 100,000 m3 per annum | 0.8 | 4.73 |
| Bio Fuel Plant | 100m litres per annum | 0.8 | 1.00 |

*Source:*
a. *Biogas plant based on typical small scale unit; biofuels plant based on larger scale biofuels plant producing 30 million US gallons annually. See http://www.agmrc.org/renewable_energy/ biodiesel/biodiesel_economics__costs_tax_credits_and_coproduct.cfm*
b. *Based on conventional refinery performance*
c. *Based on announced investment costs for biofuel plants in the US*

**Table 3.14 Definition of Biofuel Plant Types**

Plant retirement / replacements are calculated as previously.

### 3.6.3 Building the Characteristics of the "Project Capsules"

For each category of investment, hydrogen, electricity, gas etc., certain data is defined for use elsewhere in the model. In effect these are used to define individual "Project Capsules" which can be drawn down by the companies making the investments and serve to meet demand.

#### 3.6.3.1 Definition of initial assumptions and policy measures

A number of fundamental assumptions have been made with respect to the general environment and the policy settings and these are made available to the model. These can be altered by the user in order to explore different scenarios although some of the technical data would be immutable. The key economic assumptions are provided in Table 3.15.

| Parameter | Base Value | Comments / Source |
|---|---|---|
| Growth in Energy Demand | 0.50% | Based on Scottish Government Projections and represents the increase in demand over and above a basket of “normal” efficiency improvements which would serve to reduce demand, e.g. better insulation [24] |
| General Price Inflation | 2.0% | Based on historical RPI, average for last 10 years (Source: National Office of Statistics) |
| Energy Price Inflation | 2.0% | Based on last 10 years (Source: Department of Energy and Climate Change) |
| Wage Inflation | 2.0% | Based on average last 10 years (source: National Office of Statistics) |
| Marginal Corporation Tax Rate | 30% | Current prevailing tax rate 2009 (Source: HM Revenue and Customs) |
| GBP / USD Exchange Rate | 1.49 | Based on average rate over last 12 months as at 30 April 2010 (Source: www.xe.com) |
| GBP / EUR Exchange Rate | 1.12 | Based on average rate over last 12 months as at 30 April 2010 (Source: www.xe.com) |
| LIBOR | 5.5% | Average rate for 3 month LIBOR over the last 10 years ([6]) |
| Project Finance Debt Premium (basis points) | 100 | Average rate for projects of this nature (Source: Project Finance) |
| Risk Free Rate of Interest | 4.3% | Coupon on 20 year UK government bond, ([22]) |
| Market Return | 6.1% | Based on compound annual performance of FTSE 100 market over the last 20 years (Source: DataStream) |

**Table 3.15 Basic Economic Data Utilised by the Model Calculations**

All prices and costs used in the model are expressed in nominal terms and inflated according to the appropriate rate of inflation in each period modelled. In addition to the economic aspects considered, the model requires a certain amount of technical data relating to the types of fuel explored as shown in Table 3.16.

| Energy Source / Vector | Parameter | Base Value |
|---|---|---|
| Natural Gas | Density @ STP in kg / $m^3$ | 0.72 |
| | Lower Heating Value in kWh / $m^3$ | 7.59 |
| | Emissions in kg / kWh | 0.20 |
| Biogas | Density @ STP in kg / $m^3$ | 0.72 |
| | Lower Heating Value in kWh / $m^3$ | 7.59 |
| Petrol / Diesel | Density @ STP in kg / litre | 0.78 |
| | Lower Heating Value in kWh per litre | 9.70 |
| | Emissions in kg / kWh | 0.25 |
| Hydrogen | Density @ STP in kg / $m^3$ | 0.09 |
| | Lower Heating Value in kWh / $m^3$ | 33.40 |

Source: Perry's Chemical Engineers Handbook, Seventh Edition, McGraw-Hill Professional

**Table 3.16 Technical Data Relating to Different Fuel Types**

The base case energy prices are based on either the wholesale price, in the case of oil, natural gas and electricity, or what is referred to as the "supplier price", in the case of transport fuels. While a wholesale market for petrol exists the author wished to capture the effect of the increased efficiency at the application level implied by a shift to hydrogen and fuel cell based transportation, hence the use of the "supplier price", defined by Equation (3.9).

*Supplier Price = Retail Price – VAT – Margin – Fuel Duty* **(3.9)**

where

*Supplier Price* = Price received by the primary supplier, in currency units
*Retail Price* = Price paid at the "pump" by the consumer, in currency units
*VAT* = Value Added Tax (17.5% at the time of developing model), in currency units
*Fuel Duty* = tax payable on fossil fuel, in currency units

The base case prices used in developing the model are provided in Table 3.17.

| Fuel / Energy Type | Base Case Price in pence per kWh | Source |
|---|---|---|
| Wholesale Natural Gas | 1.5 | NYMEX market |
| Wholesale Electricity | 2.5 | Elexon |
| Petrol (Supplier) | 2.7 | Average pump price last 5 years as reported by the AA |

**Table 3.17 Energy Prices per kWh in 2010 (Base Case Scenario)**

A number of other core assumptions are made such as those relating to the expected capacity factors of different equipment types but these are discussed elsewhere in the Thesis where they can be more pertinently related to the discussion. The policy parameters used in the model are defined in Table 3.18. Once again, as was previously discussed in Section 2.4.3.1, hydrogen does not currently qualify for the RTFO but it has been assumed in the model that this benefit is in fact applied, reflecting the expectation that support will be provided to hydrogen fuel once it is considered to be a technically viable alternative. It will be shown in Section 4.1.2 that the performance of the hydrogen production units are relatively sensitive to the RTFO price and consequently hydrogen's inclusion in the legislation or not is of critical importance. The benefit is applied throughout the modelling period to renewably produced hydrogen and for the period 2010 – 2014 for "brown" hydrogen.

| Parameter | Base Value | Comments / Source |
|---|---|---|
| **Carbon Taxes / Prices** | | |
| Price of Carbon (ETS, pence per kg $CO_2$) | 10.7 | Based on average price for last 90 days as at 30 April 2010 ([40]). |
| **Electricity Certificates** | | |
| ROC Price (£ / MWh) | 35.0 | Based on buyout price for 2008 / 2009 period (Source: NPFA) |
| Onshore Wind Power (1 ROC) | 35.0 | Allocation of ROCs according to Renewables Obligation (Scotland) 2009 (http://www.opsi.gov.uk/legislation/scotland/ssi2009/draft/sdsi_9780111003268_en_1). |
| Offshore Wind Power (1.5 ROC) | 52.5 | As above |
| Wave Power (5 ROC -> 1 in 2050) | 175.0 | As above. Tapering based on step function and expectations regarding length of time support levels prevail |
| Tidal Power (3 ROC -> 1 in 2040) | 105.0 | As above |
| Coal Plus CCS (1.5 ROC -> 1 in 2070) | 52.5 | Allocation of ROCs based on assumptions about viability and current conditions of Scottish Renewables Obligation (Scotland). Tapering based on step function and expectations regarding length of time support levels prevail |
| **Current UK Transport Duty / Transport Certificates** | | |
| Duty Rate (2009) in pence per litre | 54.2 | Source: HM Revenue and Customs |
| Bio fuel duty differential in pence per litre | 20.0 | Source: HM Revenue and Customs |
| Price of RTFO Buyout (pence per litre of petrol equivalent) | 15.0 | Source: UK Government Renewable Transport Fuels Obligation Order (2007) http://www.opsi.gov.uk/si/si2007/uksi_20073072_en_1 |
| Total Benefit (duty reduction + RTFO Buyout) | 35.0 | |
| Fossil Hydrogen Benefit | 35.0 | Benefit applies to in period 2010 - 2014, after which it reduces to 15.0 |
| Renewable Hydrogen | 35.0 | Benefit applies throughout the period modelled |

**Table 3.18 Policy Parameters Utilised by the Model Calculations**

### 3.6.3.2 Building the Profit and Loss statement

Initially the Profit and Loss (P&L) for a capsule is drawn up for any given year as shown in Table 3.19.

| | |
|---|---|
| **Income** | |
| Revenues | Equal to the (volume of sales) x (price). The pricing is made with reference to current prices, the energy price inflation defined in Section 3.6.3.1 and, where applicable, the relative efficiency improvements attributable to a given technology. It is assumed that the entire capacity is sold and at the same price in any given period. |
| Revenue Enhancements | These represent incentives (such as ROCs) which serve to increase the overall revenues by, e.g. offering a price uplift for carbon neutral fuels. |
| **Costs** | |
| Input Energy Costs | The input energy volume is calculated based on the output and conversion efficiency while the cost is then calculated based on the input energy price as set out in the Price Scenarios sheet. |
| Staff Costs | Based on the (number of employees) x (average salary) defined on the Assumptions Sheet; the salary is inflated according to the wage inflation factor. |
| Other variable Costs | Calculated to be 5% of revenues |
| Fixed Costs | Based on a defined figure in year 0 and inflated according to the general RPI figure provided on the Assumptions Sheet |
| Total Operating Costs | The total costs are calculated by summing the above costs and then multiplying by an efficiency improvement factor defined for each type of capsule. This factor encompasses learning effects, scale effects and so on. |
| **Profits** | |
| Earnings Before Interest, Taxes, Depreciation and Amortisation (EBITDA) | Given by (Total Revenues) – (Total Costs) |
| Depreciation | Calculated on a straight line basis over the defined depreciation period and according to the complete Investment Cost. Note this is invariant over the depreciation period. |
| Interest | Calculated based on the Benchmark WACC |
| Income Tax | Income Tax = (Pre-Tax Profit) x (Corporation Tax Rate) which is defined on the Assumptions Sheet. Pre-Tax profit is given by EBITDA less depreciation and interest. The figure shown in the spreadsheet is only valid for that given year |
| Carbon Tax | This is a tax related to the carbon emissions associated with the consumption of the fuel in question. It is a cash item and not income tax deductible. |
| Basic Earnings | Basic Earnings = EBITDA – Depreciation – Interest – Income Tax – Carbon Tax |

**Table 3.19 Description of Profit & Loss Statement Line Items**

#### 3.6.3.3 Capital cost

The capital costs of energy production plant are given in Section 3.6.2 and are estimated with reference to a variety of sources as described. Each item of plant has learning characteristics assigned to it in the module definition sheets. The cost of the plant in the first year of the analysis period is defined together with the reference year to which that cost applies, i.e. 2010 in the basic analysis. The learning coefficient is defined according to the nature of the technology and the degree of maturity allowing the cost evolution to be calculated according to Equation (3.10) [144].

$$C(Q) = C_0 \times Q^{-\alpha} \qquad \textbf{(3.10)}$$

Where:

$C(Q)$ = the cost per unit after the production of Q units, in currency units

$C_0$ = initial cost before any units are produced, in currency units

Q = cumulative number of units produced

$\alpha$ = learning coefficient

It is important to note that the learning coefficient is defined with reference to the number of units of a particular type of plant and not time although it may reasonably be imagined that there would be a relationship between the two parameters. The cost evolution Worksheet (see Figure 3.21) takes the initial cost data, reference year and learning coefficient and combines it with a measure of the cumulative number of units produced. This is based on a multiple of the cumulative number of units produced to satisfy Scottish demand on the basis that the benefits of producing such plant in other markets would be felt in developing plant in Scotland (i.e. the Scottish market is not completely isolated and development of infrastructure is going on elsewhere). The chosen multiple relates to the relative sizes of the UK and Scottish energy markets but reflects the relatively lower penetration of hydrogen into the UK market as a whole. The logic here is that it is not considered realistic that Scotland could develop hydrogen infrastructure completely in isolation for the private vehicle fleet but that it may be reasonable to suppose that Scotland could develop the infrastructure more quickly.

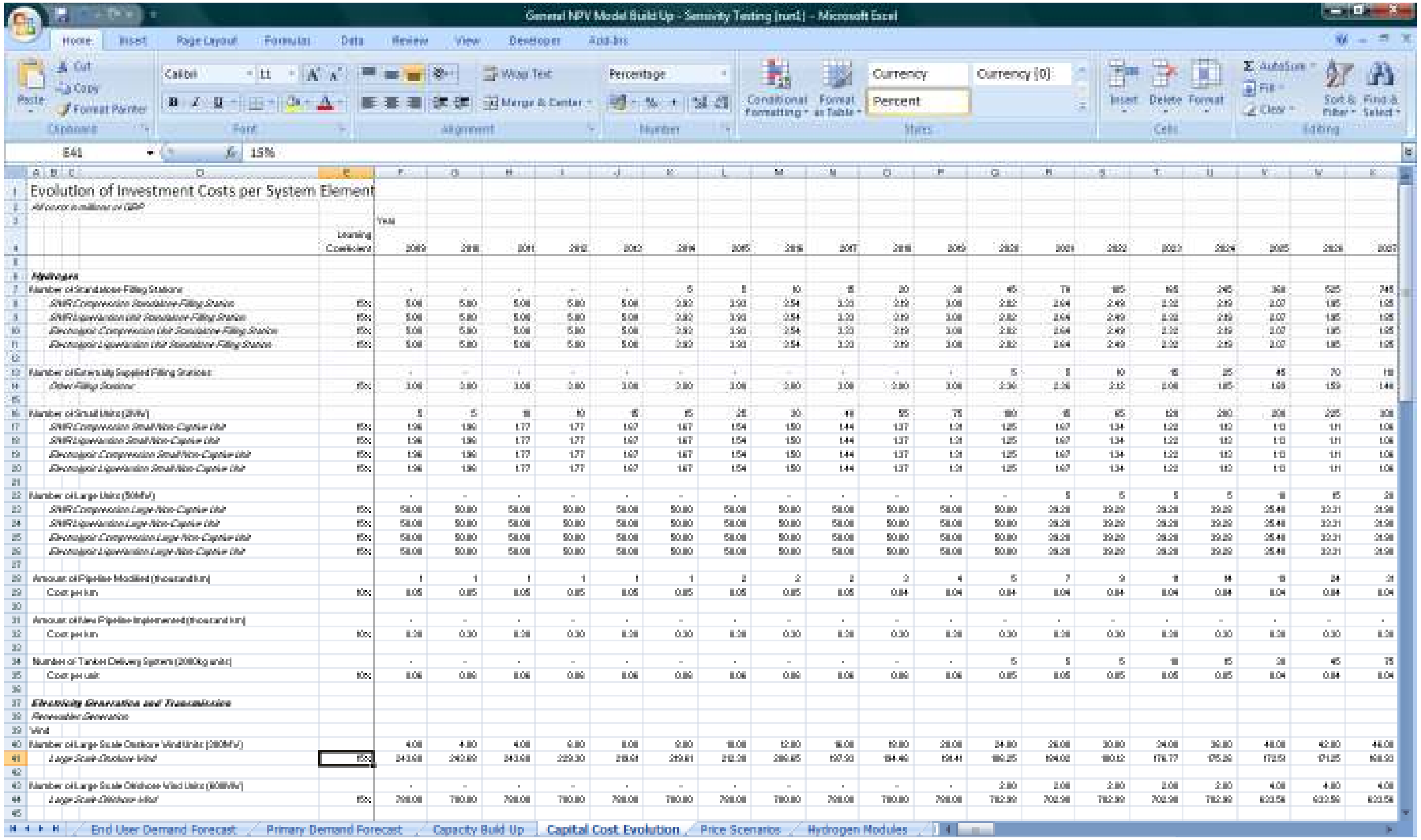



**Figure 3.21 Screenshot of Cost Evolution Worksheet**

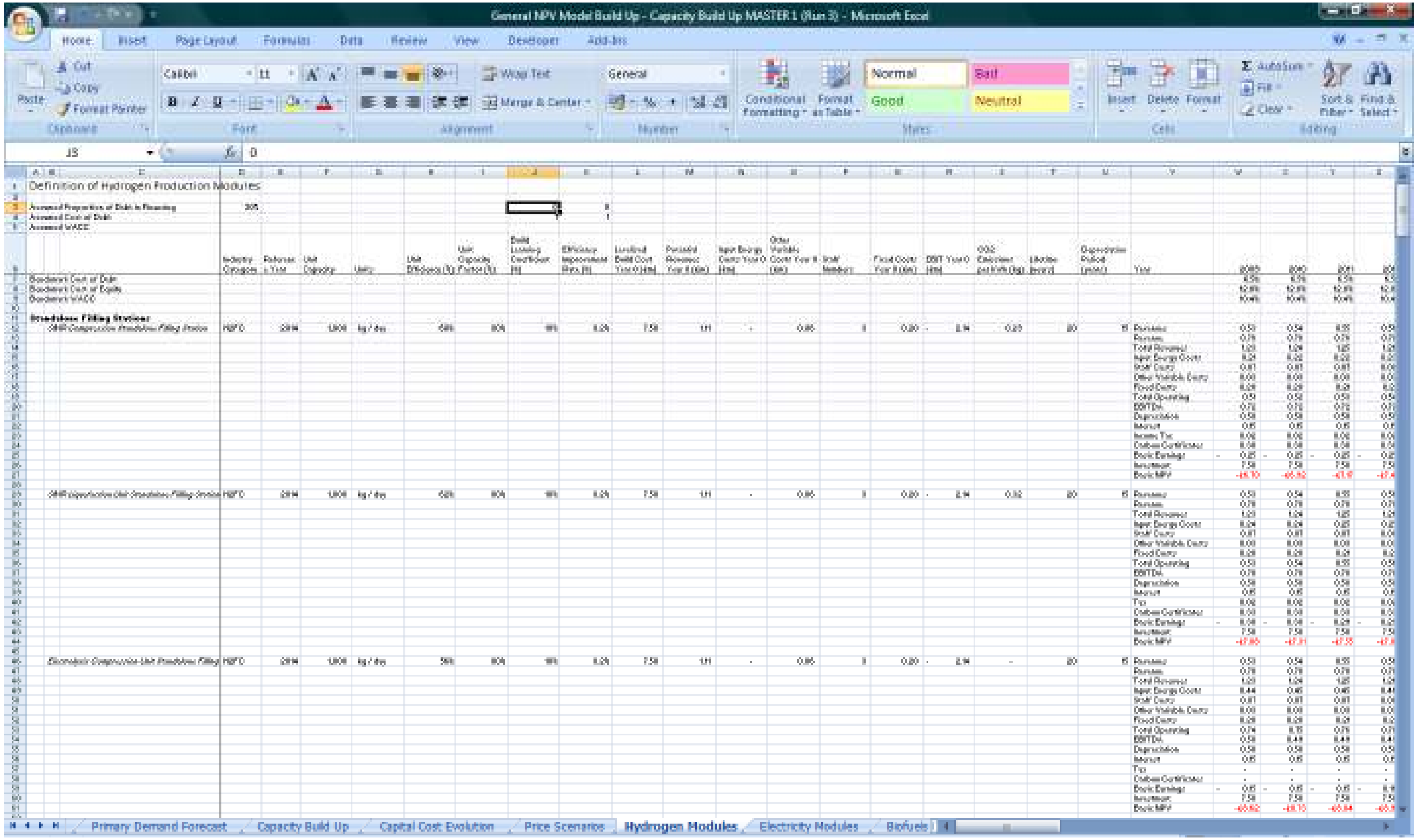



Figure 3.22 Screenshot of Module Data Worksheet Including Techno-Economic Data and Pro-Forma Profit and Loss

It is important to consider that the model assumes that the potential benefits in terms of learning or economies of scale or scope will indeed be realised as companies invest in plant and technologies. However, a conundrum nevertheless exists since if no company decides to invest the cost reduction benefits will not be achieved and the costs will not fall low enough to achieve positive NPVs. The model effectively manages this aspect partly through the application of higher support levels in earlier years which decrease over time and makes an implicit assumption that other measures designed to fund technology development, for example, through grant aid is available.

#### 3.6.3.4 The P&L and cash flow statements

A pro-forma P&L is calculated for each and every year up until 2090 while the NPV is calculated for each year up until 2050 and the data stored in an array, called projectCapsules within the Macro. The primary purpose of the projectCapsules array is to store the cashflow, revenue and earnings information so as to reuse it in calculating the value contribution to each of the companies. The process is repeated for each type of module within each primary domain, namely hydrogen, electricity, renew / heat and biofuels. An example data sheet and P&L is shown in Figure 3.22.

### 3.6.4 Introducing the Companies

The final aspect of the model is the definition of the characteristics of the companies that will be analysed. A total of some 55 companies have been monitored by the author over the period of research in order to assess changes in the metrics associated with company performance, financial stability and returns. Historical data has also been gathered in order to extend the period of analysis over as long a range as possible however a number of comments in respect of the temporal aspects of the data should be made at this point.

The first is the relationship between the timing of company results announcements and the share price. Investor expectations of share price will be based largely upon their expectations of company performance so it is critical that the most recent set of performance data is used when assessing the valuation and returns data. In the US financial data for public companies is published quarterly whereas in the UK and much of Europe results are only published every 6 months. There is also a delay in producing quarterly or half yearly results as data must be collated after the end of the period. Thus in preparing the valuation indicators, the Last Twelve Months (LTM) data is referred to which is the most recent twelve months for which data is available.

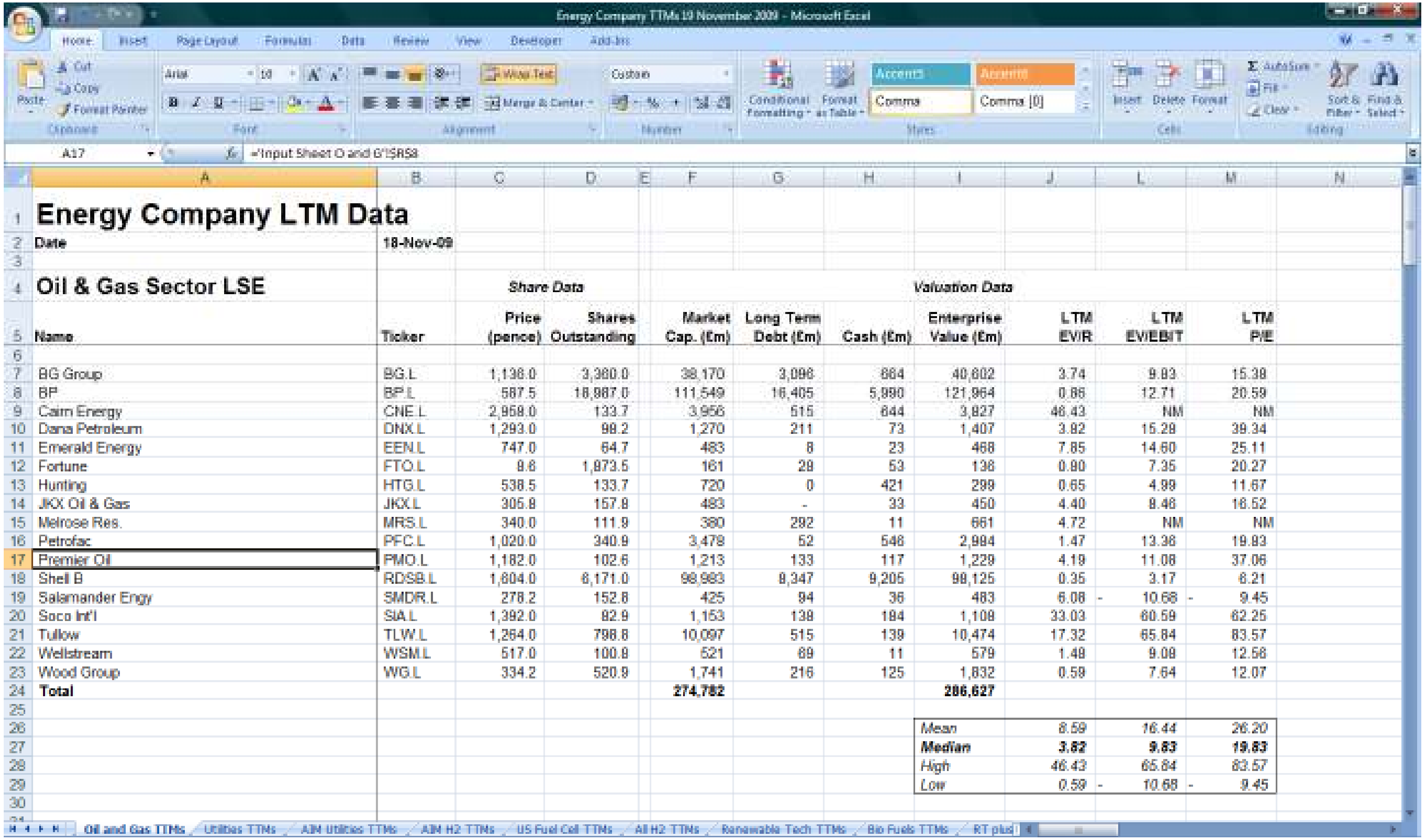
The other aspect is the variability of share price data over time. Since the share price of a company will follow a random walk, it is almost certainly misleading to use a share price on a given day when calculating valuation data. It is therefore logical to take an average share price over a period of time and for the purposes of this analysis the average price over the previous 90 days is taken. This corresponds to the quarterly regime of performance reporting followed in the US and allows a common approach to be employed for both US and European companies.

Data can be divided into Performance Indicators, Financial Indicators and Valuation and Returns Indicators and a description of these is provided in Table 3.20. Performance Indicators provide a measure of business revenue size and growth as well as margins at the EBIT and Net Earnings level. Financial Indicators represent a measure of the balance sheet characteristics of the firm. This includes net financial liabilities, outstanding share capital and cost of capital statistics. Finally, Valuation and Returns Indicators offer absolute measures of market capitalisation as well as comparative measures of returns performance and valuation multiples.

In light of the volume of data involved, the share price data and company indicator data are held in separate Excel Workbooks which are again separate from the main model. Data links are provided so that updates to data flow through from one Workbook to another. Screenshots of Worksheets from these two Workbooks are shown in Figures 3.23 to 3.25.

| | Indicator | Description |
|---|---|---|
| **Performance Indicators** | LTM Revenues (£m) | Total sales revenue in last 12 month period |
| | *LTM Growth (%)* | Growth in last 12 months revenue over previous 12 months |
| | LTM EBIT (£m) | Earnings before interest and tax in last 12 month period |
| | *EBIT Margin (%)* | EBIT in last 12 months divided by last 12 months revenue |
| | LTM Earnings (£m) | Earnings attributable to shareholders in last 12 month period |
| | *Net Margin (%)* | Earnings in last 12 months divided by last 12 months revenue |
| **Financial Indicators** | Fully Diluted Shares Out (m) | Common shares in issue or to be issued under option schemes at last balance sheet date |
| | Cash (£m) | Cash and cash equivalents at last balance sheet date |
| | Long Term Debt (£m) | Long term structural debt (loans and bonds) outstanding at last balance sheet date |
| | Cost of Debt (%) | Interest rate on structural debt as reported in the latest financial report |
| | Market Return (%) | Expected return attributable to the "market portfolio" of shares |
| | Risk Free Rate (%) | Return on a risk free asset, e.g. government bond |
| | CAPM (%) | Expected return on equity according to the capital asset pricing model |
| | WACC (%) | Weighted average cost of capital being the weighted sum of the cost of equity (according to the CAPM) and the cost of debt |
| **Valuation / Returns Indicators** | Historic Earnings Per Share (p) | Last 12 months earnings divided by the fully diluted shares out |
| | Historic Dividend Per Share (p) | Dividend payable per share in most recent 12 month period |
| | Share Price (ave. 90 days in p) | Average price of the share over a 90 day period |
| | Market Capitalisation (£m) | Average 90 day share price times fully diluted shares outstanding as at most recent report |
| | Enterprise Value (£m) | Market capitalisation plus Long Term Debt less Cash (i.e net debt) as at last balance sheet date |
| | Ratio Debt / EV (%) | Long term debt divided by enterprise value |
| | Ratio Debt / Equity (%) | Long term debt divided by market capitalisation |
| | Enterprise Value / Revenues | Enterprise value divided last 12 months revenue |
| | Enterprise Value / EBIT | Enterprise value divided by last 12 months EBIT |
| | Price / Earnings | Share price divided by fully diluted earnings per share in last 12 month period |

**Table 3.20 Description of Company Indicator Parameters**



| Name | Ticker | Price (pence) | Shares Outstanding | Market Cap. (£m) | Long Term Debt (£m) | Cash (£m) | Enterprise Value (£m) | LTM EV/R | LTM EV/EBIT | LTM P/E |
|---|---|---|---|---|---|---|---|---|---|---|
| **Energy Company LTM Data** | | | | | | | | | | |
| Date | 18-Nov-09 | | | | | | | | | |
| **Oil & Gas Sector LSE** | | *Share Data* | | | | | *Valuation Data* | | | |
| BG Group | BG.L | 1,136.0 | 3,360.0 | 38,170 | 3,096 | 664 | 40,602 | 3.74 | 9.83 | 15.38 |
| BP | BP.L | 587.5 | 18,987.0 | 111,549 | 16,405 | 5,990 | 121,964 | 0.86 | 12.71 | 20.59 |
| Cairn Energy | CNE.L | 2,958.0 | 133.7 | 3,956 | 515 | 644 | 3,827 | 46.43 | NM | NM |
| Dana Petroleum | DNX.L | 1,293.0 | 98.2 | 1,270 | 211 | 73 | 1,407 | 3.82 | 15.28 | 39.34 |
| Emerald Energy | EEN.L | 747.0 | 64.7 | 483 | 8 | 23 | 468 | 7.85 | 14.60 | 25.11 |
| Fortune | FTO.L | 8.6 | 1,873.5 | 161 | 28 | 53 | 136 | 0.80 | 7.35 | 20.27 |
| Hunting | HTG.L | 538.5 | 133.7 | 720 | 0 | 421 | 299 | 0.65 | 4.99 | 11.67 |
| JKX Oil & Gas | JKX.L | 305.8 | 157.8 | 483 | - | 33 | 450 | 4.40 | 8.46 | 16.52 |
| Melrose Res. | MRS.L | 340.0 | 111.9 | 380 | 292 | 11 | 661 | 4.72 | NM | NM |
| Petrofac | PFC.L | 1,020.0 | 340.9 | 3,478 | 52 | 546 | 2,984 | 1.47 | 13.36 | 19.83 |
| Premier Oil | PMO.L | 1,182.0 | 102.6 | 1,213 | 133 | 117 | 1,229 | 4.19 | 11.08 | 37.06 |
| Shell B | RDSB.L | 1,604.0 | 6,171.0 | 98,983 | 8,347 | 9,205 | 98,125 | 0.35 | 3.17 | 6.21 |
| Salamander Engy | SMDR.L | 278.2 | 152.8 | 425 | 94 | 36 | 483 | 6.08 | -10.68 | -9.45 |
| Soco Int'l | SIA.L | 1,392.0 | 82.9 | 1,153 | 138 | 184 | 1,108 | 33.03 | 60.59 | 62.25 |
| Tullow | TLW.L | 1,264.0 | 798.8 | 10,097 | 515 | 139 | 10,474 | 17.32 | 65.84 | 83.57 |
| Wellstream | WSM.L | 517.0 | 100.8 | 521 | 69 | 11 | 579 | 1.48 | 9.08 | 12.56 |
| Wood Group | WG.L | 334.2 | 520.9 | 1,741 | 216 | 125 | 1,832 | 0.59 | 7.64 | 12.07 |
| **Total** | | | | **274,782** | | | **286,627** | | | |
| | | | | | | | *Mean* | 8.59 | 16.44 | 26.20 |
| | | | | | | | ***Median*** | **3.82** | **9.83** | **19.83** |
| | | | | | | | *High* | 46.43 | 65.84 | 83.57 |
| | | | | | | | *Low* | 0.59 | -10.68 | -9.45 |

Figure 3.23 Screenshot from Output Worksheet for Last Twelve Month: Oil & Gas Companies

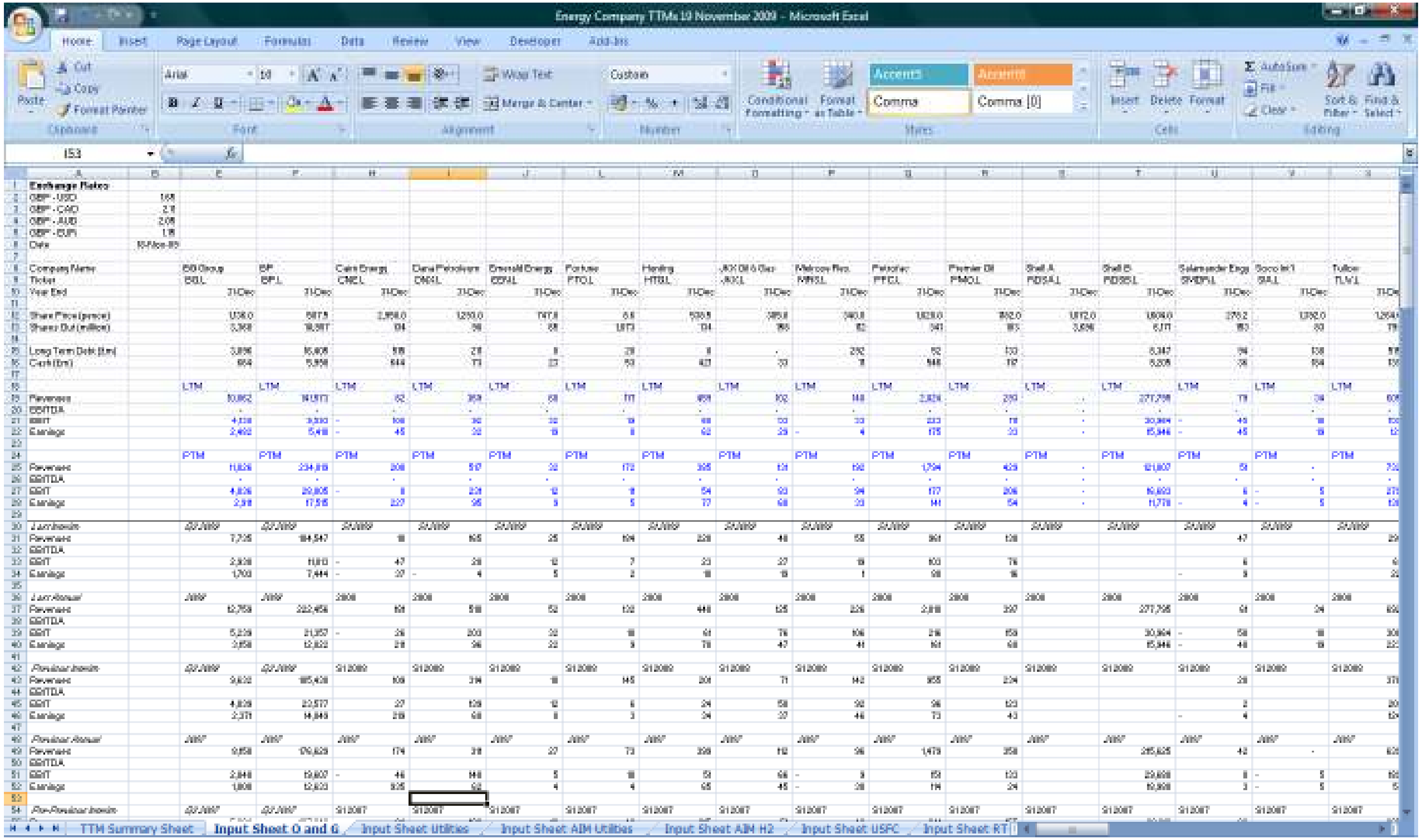



**Figure 3.24 Screenshot of Input Data Sheet for Last Twelve Month Calculations: Oil and Gas Companies**

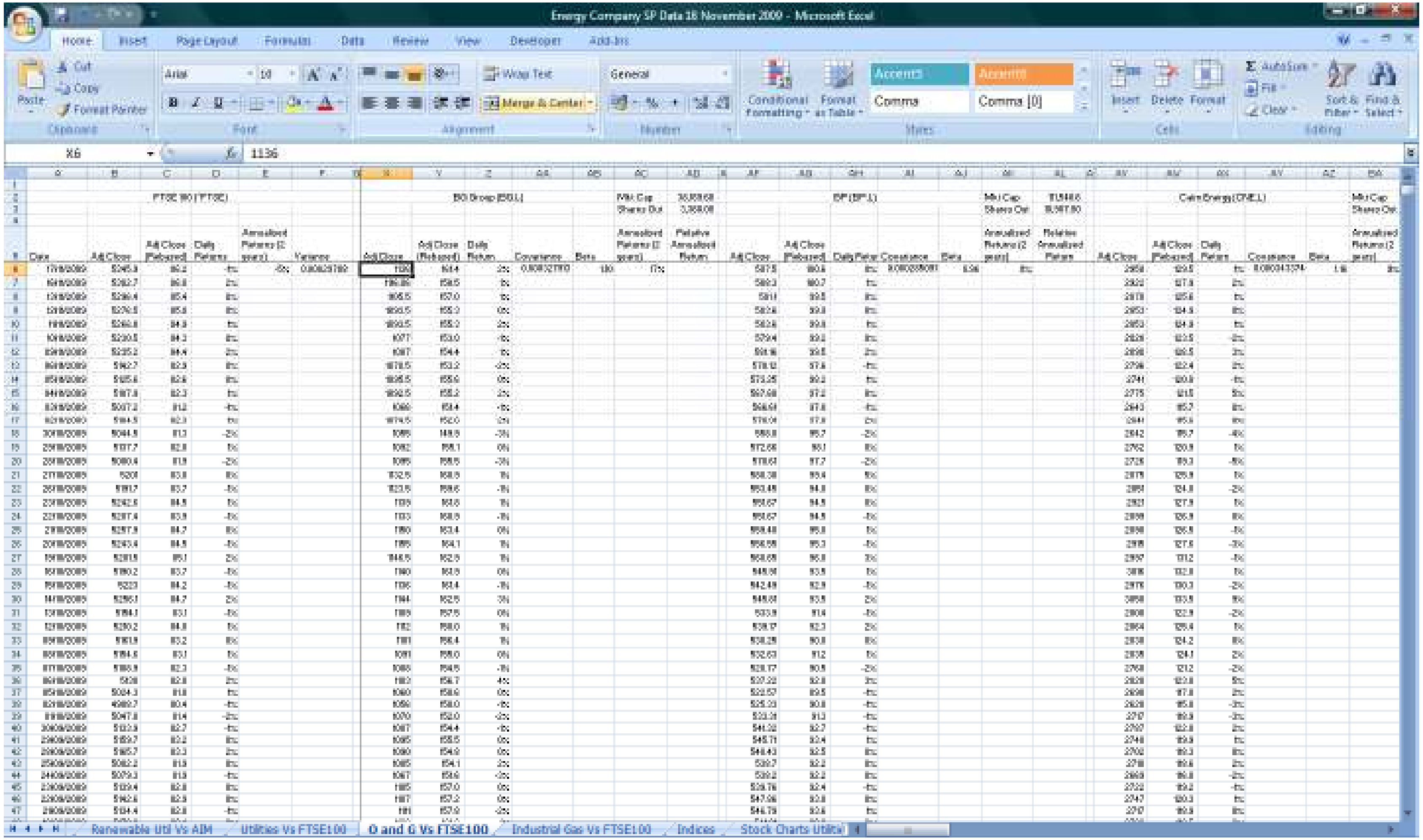



Figure 3.25 Screenshot of Share Price Data Worksheet

#### 3.6.4.1 Discussion of share price variation over time

Graphs showing the share price performance for a wide range of the companies that the author has been tracking during the 3 year period of research appear in Appendix 7.3. In each instance the graph is rebased to the start date and the performance of the relevant market is included by way of a reference point. Almost all the companies across all the sectors demonstrate a high degree of price volatility, the exception being those highly illiquid stocks quoted on the AIM market, notably Idatech. Considering the overall performance, as measured by the stock price at the end of the period in relation to the price at the start of the period, it is observed that while companies in the oil and gas and industrial gases sectors have generally shown gains, companies in the newer sectors and, somewhat surprisingly, the utilities sector have almost all posted losses. This no doubt reflects the high oil prices which have prevailed throughout the period. Nevertheless, taken as a whole, performance has been highly variable with periods of falling share prices across all sectors. By far the worst performing sector is hydrogen and fuel cells, both in the UK (AIM) and North America (mostly NASDAQ) which can probably be explained by the relatively less positive policy environment for hydrogen and fuel cells, especially when compared with the previous period of strong policy support, particularly in the US. Furthermore, there has been a consistent failure amongst the companies themselves to meet their own targets and objectives (see www.streetinsider.com for example newsflow [145]) the companies having, almost without exception, failed to generate significant revenues or any profits. The other aspect to consider is the performance of the companies relative to the market. All the markets considered here (FTSE 100, AIM All Share and NASDAQ All Share) have shown losses over the period to varying degrees as can be seen from the charts. Considering again the sectors, all but 1 of the industrial gases and the oil and gas companies have outperformed the market confirming the picture of relatively more positive investor sentiment. By contrast, all but 2 of the utilities and renewable utilities have underperformed the market. Turning to the hydrogen and fuel cell sector, all the US companies have underperformed the market whereas in the UK all but 2 underperformed. In summary, investor sentiment towards both the utilities sector and hydrogen and fuel cells sectors has been generally negative whereas sentiment towards the oil and gas and industrial gases sector is more positive.

#### 3.6.4.2 Variation of multiples data over time

The multiples data (PE and EV / R) has been observed at various points throughout the period of research and the trends for individual companies and, more importantly, sectors observed. The multiples observed in each of the sectors of interest are an input to the model and details are provided in Table 3.21. While the multiples applicable to the more established industries, i.e. traditional utilities, oil and gas and industrial gases sectors, have remained reasonably stable over the period of analysis, those for the emerging sectors have changed dramatically. These changes may be explained by factors including the relative maturity of these sectors with respect to traditional ones, the characteristics of the companies themselves and, in certain instances, the markets on which they are listed. What is clear is that the relative sentiment of investors towards the emerging markets would appear to have become more negative, as evidenced by reducing multiples. By definition, the decline in the multiples can be explained either by a relative decrease in the value of companies in the sector or a relative increase in the revenues / earnings. The share price graphs referred to in Section 3.6.4.1 clearly demonstrate the severe downward pressure on equity values in the hydrogen and fuel cell sector and in light of the relatively modest revenue growth of sector companies, it is the decline in share prices that is the primary explanatory factor of the decline in the multiple. What this indicates is that investor sentiment towards the sector (or at least a proportion of companies in the sector since this is a median value) is worsening which can be attributed to their expectations regarding growth and margins being less positive. Table 3.22 provides the company accounting data associated with the individual hydrogen and fuel cell companies which highlights their poor financial performance and goes a long way to explaining the worsening investor sentiment, either absolutely or perhaps relative to other sectors. Of course a proportion of the decline in share price may be attributed to a general decline in the share prices in the market as a whole or in the wider energy market but it is clear from looking at the relative compression of multiples that the hydrogen and fuel cell sector has been disproportionately affected.

| Sector | Market | 12 Nov '07 | | 15 Feb '08 | | 9 Aug '08 | | 12 Dec '08 | | 17 Jun '09 | | 19 Nov '09 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Median EV/R** | **Median PE** | **Median EV/R** | **Median PE** | **Median EV/R** | **Median PE** | **Median EV/R** | **Median PE** | **Median EV/R** | **Median PE** | **Median EV/R** | **Median PE** |
| $H_2FC$ | AIM / NASDAQ | 12.32 | NM | 13.46 | NM | 11.42 | NM | 5.28 | NM | 3.18 | NM | 4.31 | NM |
| Utilities | LSE | 1.73 | 12.21 | 1.49 | 11.68 | 2.30 | 12.81 | 2.22 | 11.00 | 1.18 | 10.85 | 1.69 | 11.56 |
| | AIM | 22.92 | NM | 25.71 | NM | 5.87 | NM | 5.03 | NM | 6.23 | NM | 6.55 | NM |
| Oil & Gas | LSE | 5.15 | 18.01 | 5.35 | 16.25 | 4.16 | 22.30 | 3.27 | 14.53 | 2.47 | 11.60 | 3.82 | 19.83 |
| Renewable Tech. | AIM | 51.47 | NM | 25.83 | NM | 2.87 | NM | 3.18 | NM | 0.09 | NM | 0.09 | NM |
| Bio Fuels | AIM | 29.12 | NM | 21.90 | NM | 0.14 | NM | 0.14 | NM | -0.18 | NM | -0.18 | NM |
| Industrial Gases | Various | 1.54 | 29.91 | 1.51 | 27.44 | 1.46 | 28.11 | 1.08 | 17.49 | 1.23 | 20.10 | 1.47 | 25.68 |

*1. AIM = Alternative Investment Market of the London Stock Exchange*

*2. LSE = Main List of the London Stock Exchange*

*3. NASDAQ = National Association of Securities Dealers Automated Quotations Market*

*4. NM = Not Meaningful*

*Source: Yahoo! Finance, Company Reports, As at 17 June 2009*
*Notes: Medians of a representative group of companies*

**Table 3.21 Sector Valuation Characteristics Based on Current Share Prices and Last Twelve Month Operating Data**

# Energy Company Share Price Data

**Date** **18-Nov-09**

| Name | Ticker | Price (pence) | Shares Outstanding | Market Cap. (£m) | Long Term Debt (£m) | Cash (£m) | Enterprise Value (£m) | EV/R | EV/EBIT | P/E | Revenues (£m) LTM | Revenues (£m) PTM | Revenues (£m) Growth | EBIT (£m) LTM | EBIT (£m) PTM | EBIT (£m) Growth | EBIT (£m) Margin | Earnings (£m) LTM | Earnings (£m) PTM | Earnings (£m) Growth | Earnings (£m) Margin |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Share Data* | | | *Valuation Data* | | | | | | *Performance Data* | | | | | | | | | | |
| **Hydrogen and Fuel Cell Sector (AIM)** | | | | | | | | | | | | | | | | | | | | | |
| Acta SpA | ACTA.L | 13.0 | 40.5 | 5.3 | 0.9 | 2.9 | 3.2 | 5.9 | NM | NM | 0.54 | 0.52 | 4% | -4.7 | -4.9 | NM | NM | -4.5 | -4.8 | NM | NM |
| Ceramic Fuel Cell | CFU.L | 13.5 | 491.4 | 66.1 | - | 12.5 | 53.6 | 65.4 | NM | NM | 0.82 | 1.81 | -55% | -20.6 | -11.6 | NM | NM | -20.6 | -11.6 | NM | NM |
| Ceres Power | CWR.L | 188.0 | 66.9 | 125.7 | - | 13.2 | 112.5 | NM | NM | NM | 0.95 | 0.72 | 32% | -9 | -6 | NM | NM | -8 | -5 | NM | NM |
| ITM Power | ITM.L | 21.0 | 102.1 | 21.4 | - | 21.8 | -0.4 | NM | NM | NM | - | 0.01 | NM | -6 | -6 | NM | NM | -5 | -4 | NM | NM |
| IdaTech | IDA.L | 79.0 | 49.5 | 39.1 | 4.2 | 0.4 | 43.0 | 11.96 | NM | NM | 3.59 | 3.08 | 17% | -13 | -10 | NM | NM | -13 | -9 | NM | NM |
| Proton Power | PPS.L | 5.3 | 82.0 | 4.3 | - | 0.7 | 3.6 | 3.93 | NM | NM | 0.93 | 0.82 | 13% | -4 | -3 | NM | NM | -3.6 | -3 | NM | NM |
| Voller Energy | VLR.L | 0.6 | 23.0 | 0.1 | - | 1.0 | -0.9 | -7.17 | NM | NM | 0.12 | 0.03 | NM | -3 | -3 | NM | NM | -3.0 | -2 | NM | NM |
| **Hydrogen and Fuel Cell Sector (NASDAQ)** | | | | | | | | | | | | | | | | | | | | | |
| Ballard Power | BLDP | 2.4 | 83.5 | 196 | 18.97 | 66.68 | 148.6 | 3.03 | NM | NM | 49.11 | 60.74 | -19% | -52.3 | -56.6 | NM | NM | -47.6 | -53.6 | NM | NM |
| Fuel Cell Energy International | FCEL | 3.5 | 70.6 | 249 | 4.53 | 32.96 | 220.2 | 2.24 | NM | NM | 98.38 | 86.10 | 14% | -75.1 | -87.1 | NM | NM | -80.6 | -89.1 | NM | NM |
| Hydrogenics | HYSG | 0.5 | 92.4 | 45 | - | 5.78 | 39.5 | 1.68 | NM | NM | 23.49 | 41.54 | -43% | -17.4 | -23.2 | NM | NM | -17.4 | -21.9 | NM | NM |
| Plug Power | PLUG | 0.9 | 129.0 | 111 | 1.22 | 24.14 | 88.0 | 6.44 | NM | NM | 13.66 | 17.72 | -23% | -99 | -76 | NM | NM | -36 | -75 | NM | NM |
| Quantum Fuel Systems | QTWW | 1.2 | 78.5 | 97 | 33.62 | 6.02 | 124.2 | 4.69 | NM | NM | 26.50 | 17.68 | 50% | -19 | -23 | NM | NM | -19 | -23 | NM | NM |
| | | | | | | | *Mean* | *9.81* | - | - | | | *-1%* | | | *NM* | *NM* | | | *NM* | *NM* |
| | | | | | | | ***Median*** | *4.31* | **-** | **-** | | | ***9%*** | | | *NM* | *NM* | | | *NM* | *NM* |
| | | | | | | | *High* | *65.42* | - | - | | | *50%* | | | *NM* | *NM* | | | *NM* | *NM* |
| | | | | | | | *Low* | *-7.17* | - | - | | | *-55%* | | | *NM* | *NM* | | | *NM* | *NM* |

*Source: Yahoo! Finance, Company Annual, Interim and Quarterly Reports*

**Table 3.22 Last Twelve Month Data for AIM and NASDAQ Listed Hydrogen and Fuel Cell Companies**

By contrast, in the renewable utilities sector there was a sharp decline in multiples between February and August 2008, admittedly from extremely high levels, but this has since stabilised. Once again, reference to the share price charts (Figures 7.1 to 7.6) and performance statistics for the companies concerned offers information regarding the reasons for the patterns observed. Stock prices have generally declined although in the most recent period have begun to recover. At the same time revenues have begun to grow reasonably strongly (median 16% for the group) counter-balancing the effect of the share price rises. Indeed, it is intuitively appealing to suppose that if investors expect a company's growth to be high then the initial valuation multiple would be high to reflect this and that as the growth is realised the multiple would gradually decline (unless there is a continued expectation of the same high growth levels). It is self-evident that any valuation differential between the new and the traditional sectors has been eroded, although a significant differential persists between these and both the traditional utilities and industrial gases sectors.

No doubt this valuation differential in part explains the continuing interest from utilities to separate the renewable parts of their businesses. Iberdrola SA spun-out its renewables business into Iberdrola Renovables as did Electricidad de Portugal and EDF of France, through separate listings. Enel of Italy did the same in 2010 and a look at the valuation figures for Iberdrola and Iberdrola Renovables reveals why. While Iberdrola trades on a pe ratio of 9.8, Iberdrola Renovables enjoys a pe of 33.4, more than 3 times greater. When Iberdrola Renovables was listed it raised some Eur 6 billion; at a pe ratio of 33.4 the implied dilution for shareholders of the parent company is one quarter (at 4.6%) of the dilution if the parent were to raise the funds directly (dilution of 19.4%).

#### 3.6.4.3 Principles of the value calculations

The data pertaining to each of the companies used in the value calculations is presented in Table 3.23. It should be noted that this is a subset of the companies monitored by the author over the research period since it was not considered appropriate to include all of them. The subset was chosen on the basis of their perceived relevance to the activities in question. For example, their active presence currently in the sector, an expressed desire to enter the sector or a current presence in Scotland. The companies chosen fall into 3 industry groupings, namely utilities, oil and gas majors and industrial gases majors. They all have a current interest either in directly supplying energy or industrial gases / liquids and they all have the sizeable balance sheets that would be required to launch the large scale capital investment proposed. The companies were chosen to be representative for the sector and where data on company performance was readily available in order to demonstrate the functioning of the model but should not be considered as an exhaustive list. For each of the companies, a separate Excel Worksheet is created in which the value-related information associated with the projects is calculated and recorded based upon the specific data pertaining to that company. Once again a short Macro is utilised in order to perform the calculations and the process is illustrated in Figure 3.26.

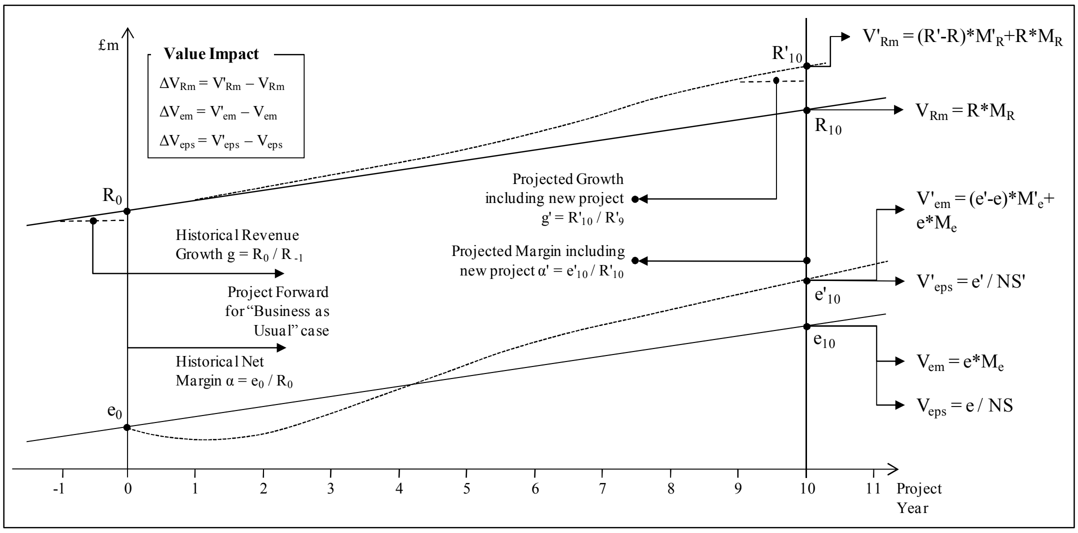



**Figure 3.26 Schematic Representation of EPS and Multiples Based Valuation Methods**

Company Performance and Valuation Data

*All amounts in GBP million unless otherwise stated*

| | Utilities | | | | | | Oil and Gas | | | Industrial Gases | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Name** | **Iberdrola** | **Iberdrola Renovables** | **SSE** | **Centrica** | **Drax** | **Intern'l Power** | **BP** | **Shell** | **BG** | **Air Products** | **Solvay** | **BASF** | **Air Liquide** |
| LTM Revenues | 23,629.5 | 1,756.7 | 24,278.6 | 21,345.0 | 1,657.9 | 3,821.0 | 141,573.3 | 277,794.5 | 10,862.0 | 5,358.5 | 7,660.9 | 45,065.2 | 11,017.5 |
| *LTM Growth (%)* | *14%* | *23%* | *29%* | *31%* | *18%* | *64%* | *-40%* | *128%* | *-8%* | *-10%* | *-19%* | *-57%* | *1%* |
| LTM EBIT | 3,664.9 | 560.5 | 1,899.7 | 1,942.0 | 347.0 | 1,156.0 | 9,593.3 | 30,964.2 | 4,130.0 | 540.2 | 646.1 | 2,576.5 | 1,615.5 |
| *EBIT Margin (%)* | *16%* | *32%* | *8%* | *9%* | *21%* | *30%* | *7%* | *11%* | *38%* | *10%* | *8%* | *6%* | *15%* |
| LTM Earnings | 2,094.1 | 284.4 | 1,163.6 | 903.0 | 238.2 | 667.0 | 5,417.6 | 15,946.1 | 2,482.0 | 393.3 | 207.0 | 558.3 | 759.1 |
| *Net Margin (%)* | *9%* | *16%* | *5%* | *4%* | *14%* | *17%* | *4%* | *6%* | *23%* | *7%* | *3%* | *1%* | *7%* |
| Historic Earnings Per Share (pence) | 42.8 | 6.7 | 126.1 | 21.3 | 70.0 | 39.2 | 28.5 | 258.4 | 73.9 | 184.8 | 251.0 | 60.8 | 287.3 |
| Historic Dividend Per Share (pence) | | | | | | | | | | | | | |
| Fully Diluted Shares Outstanding (million) | 4,894.9 | 4,223.4 | 922.9 | 4,233.0 | 340.4 | 1,702.1 | 18,987.0 | 6,171 | 3,360 | 212.8 | 82.4 | 918.5 | 264.3 |
| Cash | 1,814.4 | 218.3 | 711.4 | 2,939.0 | 164.6 | 1,129.0 | 5,989.7 | 9,205 | 664 | 42.6 | 500.0 | 2,548.7 | 1,119.8 |
| Long Term Debt | 20,060.1 | 3,185.7 | 4,816.7 | 3,218.0 | 319.0 | 7,026.0 | 16,404.8 | 8,347 | 3,096 | 2,276.2 | 1,360.9 | 12,441.0 | 5,395.8 |
| Book Value of Liabilities | | | | | | | | | | | | | |
| Cost of Debt | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% |
| Market Return (%) | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% |
| Risk Free Rate | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% |
| CAPM | 9.7% | 10.8% | 7.8% | 7.3% | 7.5% | 9.4% | 7.8% | 7.9% | 8.4% | 8.3% | 8.2% | 10.4% | 9.3% |
| WACC Based on 70:30 Equity:Debt split) | 8.6% | 9.3% | 7.3% | 6.9% | 7.1% | 8.4% | 7.3% | 7.3% | 7.7% | 7.6% | 7.6% | 9.1% | 8.3% |
| Share Price (average last 90 days in pence) | 546.0 | 287.2 | 1,115.3 | 241.98 | 456.05 | 270.27 | 525.9 | 1,531.5 | 1,073.9 | 5,087.0 | 6,024.4 | 3,112.5 | 6,678.8 |
| Market Capitalisation | 26,725.0 | 12,130.5 | 10,293.3 | 10,242.9 | 1,552.4 | 4,600.2 | 99,855.0 | 94,508.9 | 36,084.2 | 10,825.2 | 4,967.0 | 28,588.1 | 17,649.1 |
| Enterprise Value | 44,970.7 | 15,097.9 | 14,398.6 | 10,521.9 | 1,706.8 | 10,497.2 | 110,270.2 | 93,650.7 | 38,516.2 | 13,058.8 | 5,827.8 | 38,480.4 | 21,925.1 |
| Ratio Debt / EV (%) | 45% | 21% | 33% | 31% | 19% | 67% | 15% | 9% | 8% | 17% | 23% | 32% | 25% |
| Ratio Debt / Equity (%) | 75% | 26% | 47% | 31% | 21% | 153% | 16% | 9% | 9% | 21% | 27% | 44% | 31% |
| Enterprise Value / Revenues | 1.9 | 8.6 | 0.6 | 0.5 | 1.0 | 2.7 | 0.8 | 0.3 | 3.5 | 2.4 | 0.8 | 0.9 | 2.0 |
| Enterprise Value / EBIT | 12.3 | 26.9 | 7.6 | 5.4 | 4.9 | 9.1 | 11.5 | 3.0 | 9.3 | 24.2 | 9.0 | 14.9 | 13.6 |
| Price / Earnings | 12.8 | 42.7 | 8.8 | 11.3 | 6.5 | 6.9 | 18.4 | 5.9 | 14.5 | 27.5 | 24.0 | 51.2 | 23.2 |

*Source: Datastream, Yahoo! Finance, company annual and interim reports, Financial Times [22]*

**Table 3.23 Performance, Balance Sheet and Valuation Indicators Relating to the 13 Energy Companies**

Initially the program selects the historical growth and margin data for the company and projects revenue and earnings forward – historical growth and margins are assumed to remain constant – providing a "business-as-usual" case (lines $R_0$–$R_{10}$ and $e_0$–$e_{10}$). The projected revenue and profit from the new plant is then added to the existing projected revenue and profitability data in order to arrive at the combined revenue (line $R_0$–$R'_{10}$) and profit ($e_0$ – $e'_{10}$).The total company value both including and excluding the new project based on the "sum-of-the-parts" approach is then calculated with reference to the relevant revenue and profitability multiples according to Equations (3.11) to (3.17).

*Sum of the parts based on revenue multiple*

$$V'_{Rm} = (R' - R) \times M'_R + R \times M_R \tag{3.11}$$

$$V_{Rm} = R \times M_R \tag{3.12}$$

$$\Delta V_{Rm} = V'_{Rm} - V_{Rm} \tag{3.13}$$

where

$R_x$ / $R'_x$ = projected revenue in year x excl. / incl. new project, in currency units

$M_R$ / $M'_R$ = applicable revenue multiples

$V_{Rm}$ / $V'_{Rm}$ = value based on revenue multiple, in currency units

*Sum of the parts based on earnings multiple*

$$V'_{em} = (e' - e) \times M'_e + e \times M_e \tag{3.14}$$

$$V_{em} = e \times M_e \tag{3.15}$$

$$\Delta V_{em} = V'_{em} - V_{em} \tag{3.16}$$

where:

$e_x$ / $e'_x$ = projected earnings in year x excl. / incl. new project, in currency units

$M_e$ / $M'_e$ = applicable earnings multiples

$V_{em}$ / $V'_{em}$ = value based on earnings multiple, in currency units

The earnings per share based calculation is made in a similar way as per Equations (3.17) to (3.19).

$$V'_{eps} = \frac{e'}{NS'} \tag{3.17}$$

$$V_{eps} = \frac{e}{NS} \tag{3.18}$$

$$\Delta V_{eps} = V'_{eps} - V_{eps} \tag{3.19}$$

where

$V_{eps}$ / $V'_{eps}$ = value based on earnings multiple

NS / NS' = number of shares excluding / including new project

The results are then recorded in the individual Worksheets pertaining to each company and stored in an array so they can be utilised elsewhere in the model.

## 3.7 Model Validation

Model validation within the context of socio-economic modelling is taxing, especially when the model is built to consider long time frames, and evaluating the predictive accuracy of a model challenging, if not impossible. As Schwarz and Hoag assert [87], when comparing the validation methodologies applicable to different types of modelling:

“Validation is usually considered as an essential part of modelling work and understood to be a testing of the model by comparisons of model results either with outcomes of controlled experiments or with historical data. However, experiments involving complex socio-technical systems are difficult to design and evaluate.”

Figure 3.27 presents the continuum of modelling problems along an axis running from models requiring simple objective choices with regards to validation method and those requiring complex subjective choices [146]. At one end of the spectrum, are what might be termed scientific models that can be validated against precise mathematical laws and where results can be attained with strong predictive accuracy. At the other end of the spectrum, are socio-economic models where the predictive accuracy is poor and the representation of reality subjective.

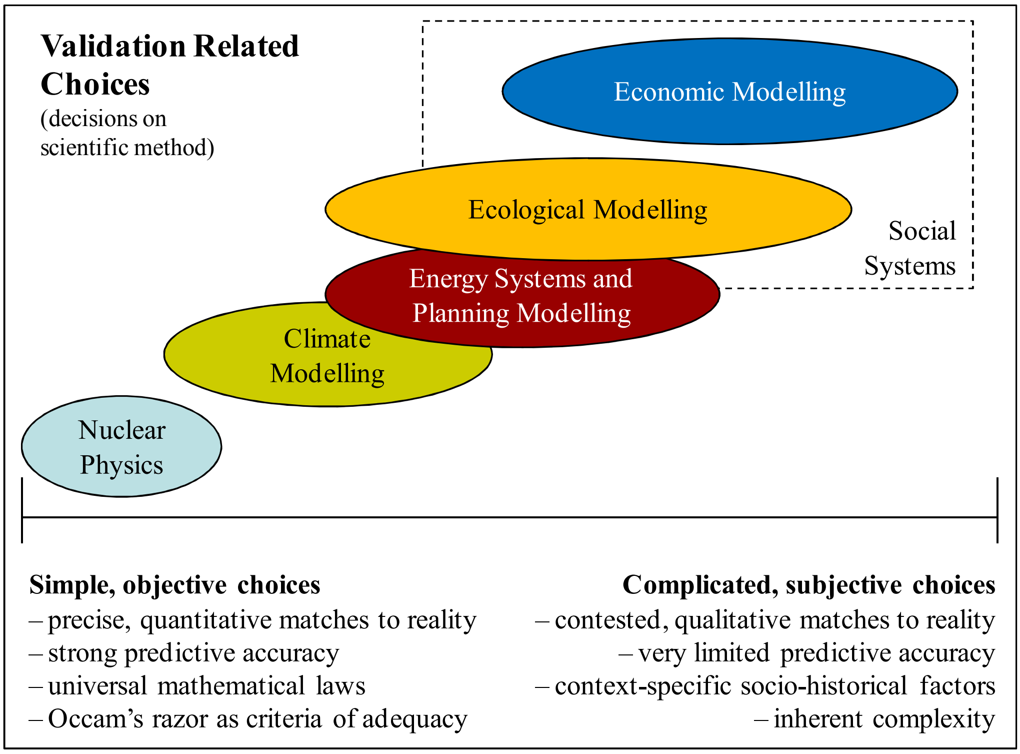



**Figure 3.27 Typical Validation Choices According to System Type**

Philosophically speaking, the approach taken and the validity attributed to a given model might reflect the dogmas of particular disciplines (Kuhn’s competing paradigms [147]). In some instances these are discussed explicitly in the literature, especially the social simulation literature, while in other fields the researcher's or the school's views on these are often only *implicit* in the definition of the model and experimental process. Thus in some sense the generally accepted practice in a given discipline will affect how valid observers consider a new model to be. Hence, the author has used validation methods “acceptable” to the energy modelling discipline.

### 3.7.1 Specific Issues

A number of specific issues relevant to the issue of validation arise when considering the author’s model. These issues are commonly encountered by those developing this sort of non-technical simulation and are described in the following sections.

#### 3.7.1.1 Time lag to obtaining empirical outcome

Since the model attempts to predict results far into the future there is a significant time delay from when the forecast is made to when the actual outcomes are realised and can be measured. While it might be argued that over time data regarding the predictive accuracy can be built up, at the outset this is not feasible.

#### 3.7.1.2 Modelling a new domain

One possible solution to the temporal issue discussed in Section 3.7.1.1 would be to apply the model to some historical data with a view to developing a “forecast” over the period immediately prior to the present day and comparing this with empirical data. While there might be significant challenges associated with gathering the appropriate data such an approach would be theoretically possible for an existing market. For a new market, no such empirical data exists and it might be considered inappropriate to try to force such a validation through testing the model against an analogous market [87]. In any case, it is uncertain how such an analogue would be chosen and still satisfy the condition of model plausibility as will be discussed in Section 3.7.2.5. The author considered that the uncertainties associated with the selection of a suitable analogue and the in light of the issues surrounding variability of results that the application of such a method would not be meaningful. Nevertheless, such a study could form the basis of future investigations.

#### 3.7.1.3 Variability in results

Since the model does not pretend to be deterministic, and it is argued that no such model can be, the output by definition will encompass a range of possible values according to a probabilistic distribution as discussed in Sections 3.5.3.1 and 3.5.3.2. In consequence, even if the actual outcome does not correspond with the central prediction from the model (e.g. within 1 standard deviation either side of the mean) that does not necessarily invalidate the model itself but simply indicates that the actual result was an outlier. Indeed, it is questionable whether validation against historical data is meaningful if it is suspected that the real world system's actual path was governed by rather unlikely events, i.e., the model provides a realistic picture but the actual outcome represented a very statistically unlikely situation.

### 3.7.2 How the Author's Model is Validated

It is interesting that MARKAL has not been subject to historical validation as discussed once again by Schwarz and Hoag [87]. Given the role that MARKAL, and the author's model have in considering new and significantly altered systems, such validation may be inappropriate as others have highlighted. In light of the issues described, the author has employed a number of validation techniques which are described in the following sections.

#### 3.7.2.1 Confirmation of basic theory

The first stage is the verification of the basic principles used in the construction of the model. This has both "technical" aspects such as how to calculate the Net Present Value of a series of future cashflows and some behavioural aspects such as what drives strategic decision-making. The first is relatively easy to achieve through reference to the relevant equations while the second is achieved through reference to literature in the field. Both these aspects have largely been covered already in Chapter 2.

#### 3.7.2.2 Triangulation of input data

The second level of validation is at the level of the input data. In each case at least one referenced and verifiable source is used as the basis for the input data and if possible any data is confirmed through a second source. Particular attention has been paid to the credibility of the sources for the input data.

#### 3.7.2.3 Validation of the implementation

At each stage the formulae within the spreadsheets have been verified and tested, for example by measuring the changes to the output of cells as the inputs are varied. Since the construction of the model is highly modular in nature it has been possible to test each module separately as well as the functioning of the modules with one another.

#### 3.7.2.4 Internal testing

In terms of the Visual Basic programs these have been tested at two levels. Firstly, the usual careful verification of the code was carried out and the use of a modular construction minimised the possibility of errors. Secondly, the key calculations have been verified "manually" using equivalent Excel functions to replicate the results.

#### 3.7.2.5 Testing plausibility

Having considered the more objective assessments of the model, the plausibility of the results has next been considered on two levels:

1. Do the results concur with basic expectations? For example, if the discount rate is increased does the NPV decrease and, if not, is there a satisfactory explanation? This is a relatively objective assessment criterion although it does require a degree of user interpretation especially where complex calculations interact with one another.

2. Do the results appear to be "reasonable"? Needless to say this hinges on the interpretation and judgement of the user and does not purport to represent an objective assessment of the results of the model. However, this element is present in the use of all such models as many observers have discussed.

The underlying assumption is that since the model is not intended to produce quantitative accuracy against empirical data (as discussed, this is not possible as the empirical data is delayed) but can be validated against qualitative patterns sometimes referred to as "stylised facts".

## *3.8 Chapter Summary*

The analysis presented in Chapter 3 confirmed Scotland's reliance on fossil fuels and also highlighted some key differences with the UK as a whole (see Figure 3.19). In particular, Scotland is currently an exporter of electricity and has a significantly greater potential renewable resource which puts it in a potentially attractive position with respect to producing renewable hydrogen. A potentially significant "surplus" of electricity exists which could be directed to the production of hydrogen and reference to the Hyfuture [103] report provides confirmatory evidence of this possibility. The question is, would there be appetite to invest in the production infrastructure?

Some initial pointers can be drawn from reference to the relative performance and valuation metrics of companies across the energy sector including the hydrogen and fuel cells market (see Table 3.21). It is evident that energy companies have suffered mixed fortunes over the three years of the research study. While oil and gas companies have performed quite well in terms of share price performance, those in the all other sectors have suffered and those in the $H_2$FC domain have suffered the most. Considering valuation metrics, companies in the $H_2$FC market have shown compressing EV / R ratios, so much so that they barely enjoy a premium today over oil and gas companies despite being, in principle, at a higher growth stage of their business cycle.

While these companies would be expected to register growth and, ultimately improving margins, growth has instead stagnated and margins have if anything worsened. The effects of these factors on the results of the model will be discussed in more detail in Chapters 0 and 5 of the Thesis but it does provide a positive picture for the $H_2FC$ sector.

One further important aspect of the model was discussed in this Chapter, namely the validation of the model (see Section 3.7). As is the case with any such forward looking model, validation is challenging especially when historical validation seems inappropriate or unfeasible as is the case with the author's model. For this reason the processes of verifying the model's internal workings are of critical importance and a clear methodology was developed which has been discussed. To summarise, the Chapter presented:

- A brief comparison was made between the authors value-led model and the typical cost optimisation approach in order to highlight the potential differences in output. Examples were provided of how the different approach could alter the timing of investment and how it might affect interpretation of the MAC Curve (see Figure 3.5 and analysis).
- The basic processes in the author's model were described and the objective equations set out together with the model constraints in Sections 3.3 and 3.4.
- A detailed description of the model's working was provided through flow charts and screenshots and reference was made to Appendix 1, 2 and 3 where the code for the macros can be found as well as data on Scotland's generating capacity and key company data and metrics. The model was highlighted as having been created in a series of Excel Workbooks which perform some of the calculations internally and others through the use of Visual Basic Macros.
- The input data used in the Scottish implementation of the model were provided and, using this, the initial demand and supply scenarios were built up and presented in Section 3.6.

- Historical data pertaining to the companies considered in the model were presented and a discussion of the performance of the different sectors offered (see Table 3.23).
- The process of calculating the value impact of different projects on the valuation of companies in the model was described in detail.
- The proposed methods of model “validation” were discussed and commentary given on the author’s efforts to “validate” his model.

# 4 Presentation and Analysis of Results

While Chapter 3 of this Thesis provided some initial base data pertaining to the analyses to be carried out, this Chapter describes the wider set of input parameters and presents the initial results analysis and discussion.

## 4.1 Description of Analyses

### 4.1.1 General Analysis

The general economics of the plant types are measured and charted over time in order to arrive at a baseline picture of plant performance. As was discussed in Chapter 3, the key outputs to be measured relate to the revenues, cashflows, profitabilities and NPVs of different plant types in each of the analysis years. The profile of these measures is calculated and examined over the lifetime of the project (except for the NPV which is a single data point for any given project) and over the whole analysis time period (2010 – 2050). This is illustrated in stylised form in Figure 4.1, where $R_y^x$ is the revenue in year x of the project for a project commenced in absolute year y, $E_y^x$ is the earnings for the same project in the same absolute year, $CF_y^x$ is the cashflow for the same project in the same absolute year and $NPV_y$ is the NPV for a project commenced in absolute year y.

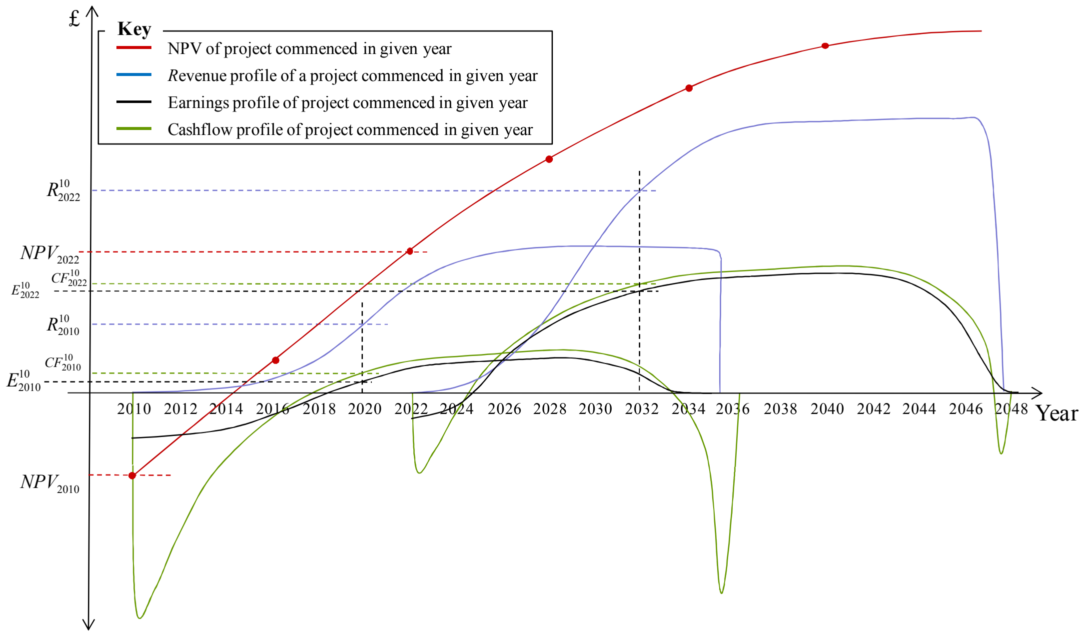



**Figure 4.1 Illustrative Chart Project Profiles and Different Values Approaches**

The red line in Figure 4.1 represents the NPV of investing in a given plant in each analysis year, in this instance with the NPV increasing over time as plant performance improves. In this example, the NPV shows that projects begun before 2014 have negative NPV but projects commenced thereafter have positive NPVs reflecting lower investment costs (lower negative dip at the start of the project) and higher revenues and cashflows at the peak. The blue lines in Figure 4.1 represent the annual revenue profile over the lifetime of a plant in which investment has been made in a particular year – in this instance two cases are shown corresponding to 2010 and 2022. The annual revenues grow from zero at the outset and follow an s-curve (in this instance, but that needn't necessarily be the case) up to a maximum value before falling to zero at the end of the project lifetime. The green lines in Figure 4.1 represent the annual cash flows over the lifetime while the black lines represent the earnings of the same two plant investments for the given plant. The cashflows for the project are initially highly negative reflecting the initial investment and then build to reach a positive value before falling to a negative value again at the end of the project reflecting the decommissioning costs. The earnings for the project, represented by the black lines in Figure 4.1 are again initially negative since it might be expected that at the outset the project revenues do not cover the costs but then turn positive as the revenues build. The earnings profile tracks the cashflow profile closely but, in this instance, has a lower value than the cashflow reflecting the depreciation charge and debt financing costs. This is also a useful illustration of how the timing chosen to compare revenues and profitability is important. Considering the 2010 project in Figure 4.1 it can be seen that the year 10 earnings are positive whereas the year 5 earnings are negative. Thus based on an EPS assessment using the year 5 earnings it might be concluded that the project is not value added while a valuation based on the year 10 earnings is more likely to suggest that it is. The relative contribution to value based on a revenue multiple would be higher in year 10 than in year 5 assuming that the multiple remains constant over time. Finally, whatever the comparison year chosen for the revenue and earnings, the NPV remains negative. For the purposes of the current comparison the revenue and earnings in year 10 of the investment have been chosen as this is considered to be when revenues and earnings will have stabilised. This has been confirmed by looking at the overall revenue and earnings profiles across the range of possible plant types investigated.

### 4.1.2 Sensitivity Analysis

Since the model is essentially bottom-up in its approach there are a very large number of input parameters all of which, when varied, will affect the outputs to some degree. These input parameters could be categorised as either exogenous, i.e. those over which the market players have little or no control, or endogenous over which the market actors do have some control. This is relevant when thinking about the relative risk since a management team of a company making a given investment might consider that those variables which are endogenous are "easier" to manage than those which are exogenous. This was discussion in Section 2.5.7 where it was argued that a shift from energy systems dependent on commodities like oil and gas to ones based around renewables could result in the application of a lower cost of capital. Implicit in the argument is that the risks are either inherently lower or, potentially, more manageable. By way of illustration, Table 4.1 presents a number of important input variables according to this typology.

<table>
<tr><th></th><th colspan="2">Variable Type</th></tr>
<tr><th>Data Category</th><th>Exogenous</th><th>Endogenous</th></tr>
<tr><td>Economic and Policy</td><td>Energy Price Inflation<br>Absolute Fuel Prices<br>Policy Instruments</td><td></td></tr>
<tr><td>Technical Plant Aspects</td><td colspan="2">Learning Characteristics<br>Efficiencies<br>Capacity Factors</td></tr>
<tr><td>Plant Costs</td><td></td><td>Absolute Capital Cost<br>Staff numbers<br>Utility costs<br>Sales and marketing costs<br>Other fixed costs</td></tr>
<tr><td>Financial</td><td>Sector Multiples</td><td></td></tr>
<tr><td></td><td colspan="2">Cost of Capital</td></tr>
</table>

**Table 4.1 Categorisation of Input Parameters According to Level of Control which Individual Companies Might be Afforded**

The objective of the sensitivity analysis is to investigate the relative impact that different variables have on the output and to calculate probability weighted outputs as described in Section 3.5.3.1. In Chapter 3 a considerable amount of data was provided relating to the base case scenarios in 2010 and this was built using existing externally referenced sources of data. However, as was discussed many aspects of the plant characteristics are still uncertain in the present day and it is reasonable to assume that the degree of uncertainty increases the further into future the analysis is extended. While in the near term it might be reasonable to make projections based on the extrapolation of historical figures the degree to which this assumption is valid diminishes into the future. As a result, a range of possible values is explored and the variation in the output as a function of the variation in the input is measured with the sensitivity indicator, as defined by Equation (4.1).

$$SI = \frac{(O_x - O_b)/O_b}{(I_x - I_b)/I_b} \quad \textbf{(4.1)}$$

where

$SI$ = Sensitivity Indicator

$O_x$ = output corresponding to input $I_x$, in appropriate units

$O_b$ = base case output corresponding to input $I_b$, in appropriate units

$I_x$ = input case x, in appropriate units

$I_b$ = base case input, in appropriate units

A high value for the sensitivity indicator suggests that the output is highly sensitive to the input and vice versa. However, care must be taken in interpreting the results since if either $I_b$ or $O_b$ are close to a zero crossing this can deliver unexpectedly high or low values for the Sensitivity Indicator.

For each input parameter investigated in the model, five separate values are assigned to that variable and the outputs measured for each of these. The variables are each altered in turn while the others are held constant at the base case value.

### 4.1.3 Probability Weighted Sensitivity Analysis

As discussed in Section 3.5.3.1, one methodology for exploring possible future outcomes is to assign a probability to each of the possible input parameter values. Through the combination of the associated output values and probabilities a single probability weighted output value is arrived at which can be used to compare different plant types (see Equation (4.2)).

$$NPV = \sum_{n=1}^{N} P_i^n \times O_i^n \qquad \textbf{(4.2)}$$

where:

NPV = Net Present Value, in currency units

N = Total number of input values attributed to input variable, i

$P_i^n$ = Probability assigned to value n of input variable i, as a fraction

$O_i^n$ = Output (i.e. NPV) obtained for value n of input variable i, in currency units

The probabilities are assigned on the basis of the author's own expectations of the market and once again these can be modified to explore different possible scenarios.

### 4.1.4 Scenario Analysis

In common with other approaches [148], scenarios which integrate a large number of input variables have been utilised in such a way as to allow a more structured analysis of the results. The four scenarios chosen by the author have the qualitative aspects described in Figure 4.2 and could be likened to scenarios developed elsewhere such as those hypothesised by the IPCC [149] describing possible global growth patterns. While the scenarios bear close similarities with others from a directional perspective, the precise details differ since in most, if not all, cases the precise input data is not made available in the public domain. The author considered the possibility of making an direct comparison with other studies made elsewhere but concluded that such an exercise would prove too challenging to perform in the timeframe available if at all.

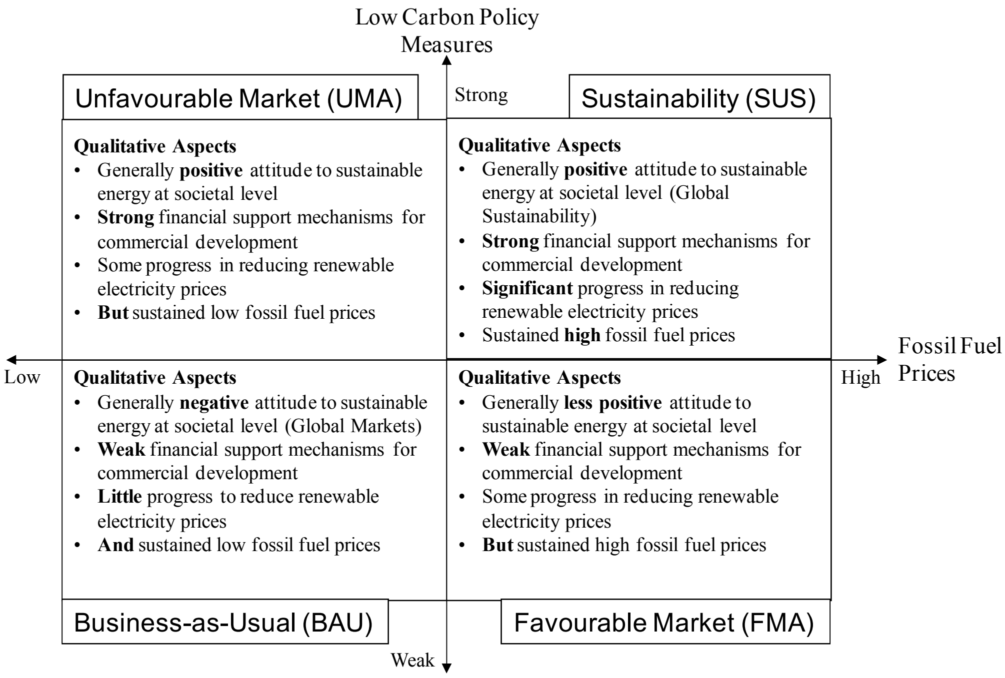



**Figure 4.2 Four Scenarios Describing Market / Environment used in Scenario Modelling**

The scenarios are aligned along two key axes, one attitudinal and one financial. The first, the Low Carbon Policy Measures axis (the y axis), describes the willingness of governments and societies to support the development of alternative energies in general and hydrogen energy in particular. Thus the two upper quadrants describe scenarios where considerable efforts are made to encourage and support these low carbon technologies through financial incentives for their uptake and / or disincentives for the use of fossil fuels. The right hand quadrants describe scenarios where the price of fossil fuels are relatively higher than current prices and therefore reinforce attempts to move towards alternatives, whereas in the left hand quadrants fossil fuel prices remain at their current levels or lower and tend to counteract any attempts to incentivise the move to alternatives to fossil fuels. The data pertaining to each of the scenarios is presented in Table 4.2.

While government incentives and market prices are the key exogenous determinants used in the scenarios, certain other assumptions are made regarding the implications that these measures would have on other input parameters. For example, it is assumed that under favourable political and / or market conditions the rate of learning and efficiency improvement for low carbon energy systems would be greater than in the unfavourable cases as more research, development and deployment grants would be available. Similarly, the model anticipates a generally more favourable funding environment (i.e. a lower cost of capital) for hydrogen and renewables in the upper quadrants as compared with the lower quadrants reflecting investor recognition of the more stable long term future development picture. The scenarios are modelled using Monte Carlo simulation in contrast to the probability weighted scenario analysis described above in order to offer an alternative perspective; this is discussed further in Sections 4.2.3 and 4.3.4.

| | SUS | | FMA | | UMA | | BAU | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Fuel Prices** | | | | | | | | |
| *Transport Fuel Price (p/ litre PE)*[a] | 180.0 | 10.0 | 180.0 | 10.0 | 90.0 | 10.0 | 90.0 | 10.0 |
| *Electricity Price (p/kWh)b* | 2.5 | 1.5 | 2.5 | 1.5 | 4.5 | 1.5 | 4.5 | 1.5 |
| *Natural Gas (p/kWh)*[c] | 3.5 | 0.5 | 3.5 | 0.5 | 1.0 | 0.5 | 1.0 | 0.5 |
| **Investment Costs** | | | | | | | | |
| *H2 Plant (percent above / below base)*[d] | -20.0 | 3.0 | -10.0 | 3.0 | -15.0 | 3.0 | +5.0 | 3.0 |
| *Electricity Plant (percent above / below base)*[d] | -20.0 | 3.0 | -10.0 | 3.0 | -15.0 | 3.0 | +5.0 | 3.0 |
| **Learning Coefficients** | | | | | | | | |
| *H2 plant (percent above / below base)*[d] | +50.0 | 2.0 | 0.0 | 2.0 | +50.0 | 2.0 | -50.0 | 2.0 |
| *Renewable plant (percent above / below base)*[d] | +50.0 | 2.0 | 0.0 | 2.0 | +50.0 | 2.0 | -50.0 | 2.0 |
| **Cost of Capital** | | | | | | | | |
| *Cost of Equity (%)*[d] | 12.0 | 2.0 | 14.0 | 2.0 | 14.0 | 2.0 | 16.0 | 2.0 |
| **Policy / Market Instruments** | | | | | | | | |
| *Carbon Price (£ / tonne)*[f] | 20.0 | 3.0 | 20.0 | 3.0 | 20.0 | 3.0 | 12.0 | 3.0 |
| *ROC (£ / MWh)*[g] | 60.0 | 5.0 | 35.0 | 5.0 | 60.0 | 5.0 | 35.0 | 5.0 |
| *RTFO plus Duty Benefit (p / litre of petrol equivalent)*[d] | 55.0 | 2.0 | 35.0 | 2.0 | 55.0 | 2.0 | 35.0 | 2.0 |

*Sources:*

*a. Based on the weekly variation in petrol price over last 5 years as reported by the AA ([74])*
*b. Based on daily variation of spot price of electricity over last 5 years as reported by Elexon ([75])*
*c. Based on daily variation of spot price of natural gas over last 5 years as shown at Nymex and reported in the Financial Times ([22])*
*d. Based on author's estimates*
*f. Based on daily variation of spot price of carbon (EUA) over last 2 years as reported by the ECX ([40])*

**Table 4.2 Means and Standard Deviations of Input Parameters to be Varied in Monte Carlo Simulation**

## 4.2 Presentation of the Hydrogen Plant Results

The results of each of the analyses described above for the hydrogen plant are presented in the sub-sections of 4.2.

### 4.2.1 General Hydrogen Plant / Project Economics

Figures 4.3 to 4.28 chart the NPV, year-10 revenue and year-10 profit performance of each of the hydrogen plant variants over the period of analysis based on a generalised level of cost of capital of 10.4% (being the WACC based on a cost of equity of 12%, a cost of debt of 6.5% and a capital structure of 70% equity and 30% debt).

#### 4.2.1.1 Refuelling Plant

Figures 4.3 to 4.7 present the performance over time in the base case scenario of the smaller refuelling station modules that have been modelled (defined as RNGC to RL in Table 3.9)

As would be anticipated, the levels of year-10 revenue are very similar across all plant since the plant all have the same capacity and these revenues increase over time owing to the energy price inflation rate anticipated by the model. The minor variations reflect the different levels of price support enjoyed by the different types of plant under the combined RTFO plus duty benefit. Since the model assumes that the electrolysis plant uses primarily renewable electricity, the level of support is slightly higher for these plant than for the steam methane reforming plant which, by definition, is a “brown” hydrogen source. The SMR plant do receive some support since they represent a partial decarbonising of the transport energy chain but at a lower level.

Despite the increasing revenues the profitability curves remain relatively flat or convex in shape with the year-10 profits being higher in the mid-years of the analysis period. To put it another way, profit margins either remain roughly constant or show some slight degradation. This reflects the fact that input energy costs increase at roughly the same rate as the price of hydrogen in the model and thus the costs roughly balance the benefits of increasing revenue. While it might be imagined that there would be a relationship between the price (and hence revenues) and the input costs the model assumes that the price will in fact be largely determined by the price of competitor fuels. Consequently there is a reduction in profitability as input energy costs increase. In the case of the SMR plant, the price of carbon also has an impact in contrast to the electrolysis plant where this does not impact for the same reason mentioned in the previous paragraph. Further, the profit margin is almost consistently negative, so while the projects might contribute to growth they are highly likely to have a dilutive effect on earnings unless business synergies could be achieved by the company undertaking the project, thus improving the overall economics of the undertaking (see Section 5.1).

Finally, as the profitability data would suggest, the NPV of these projects remains firmly negative which further confirms the non-viability of these projects to potential developers in the base case scenarios. The discontinuities observed in the early year NPVs reflect when plant starts to be introduced in the demand-side model and the related reduction in capital cost resulting from learning effects. Given these learning effects, it might be anticipated that the NPV of projects would show a consistent increase over time and indeed in certain instances this is the case. However, as here, in other cases the effects of worsening profit margins counteracts the benefits of the learning effects and causes the NPV to tail off again in later years reflecting the shape of the profitability curves.

Based on the input parameters used, the economics of the electrolysis plant are rather better than for the SMR plant which might seem inconsistent with the current accepted theory which shows hydrogen produced from natural gas to be the most economic means of production. Part of the reason for this is that the author's model assumes from the outset of the modelling period a certain degree of capital cost reduction has already been achieved for electrolysis plant. This factor only really affects the NPV analysis to any significant degree although the capital cost does have an impact on the profitability through increased financing and depreciation charges. A second aspect is the different revenue support levels enjoyed by the different type of plant which is not currently a feature of the industrial hydrogen production market. Needless to say, it is also critically influenced by the choice of input energy prices which are relatively difficult to estimate accurately since natural gas and electricity are frequently traded through private bilateral agreements at unknown prices. As discussed in Section 3.6.3.1, the prices used for wholesale gas and electricity are based on the average traded prices at the NYMEX [150] and UK Electricity Spot Market [151] respectively and may under- or over-estimate the actually prices being struck between parties in bilateral agreements. This is discussed in more detail in Section 4.2.1 describing the sensitivity analysis. One other aspect to note is that there is an underlying assumption that the hydrogen plant will use renewably produced electricity, and no allowance has been made in the initial benchmark analyses for any super-normal increase in price of electricity that might result from a significant shift from conventional to renewable sources of electricity.

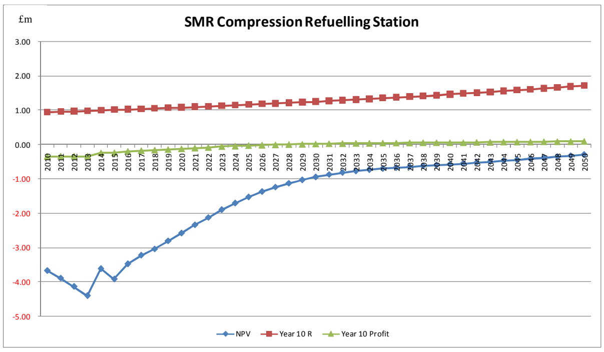



**Figure 4.3 NPV, Year 10 Profit and Year 10 Revenue for Small Scale RNGC**

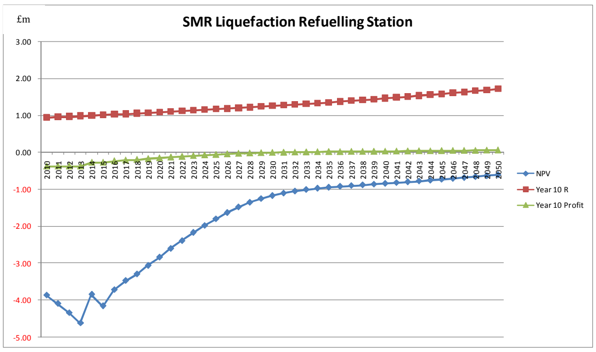



**Figure 4.4 NPV, Year 10 Profit and Year 10 Revenue for Small Scale RNGL**

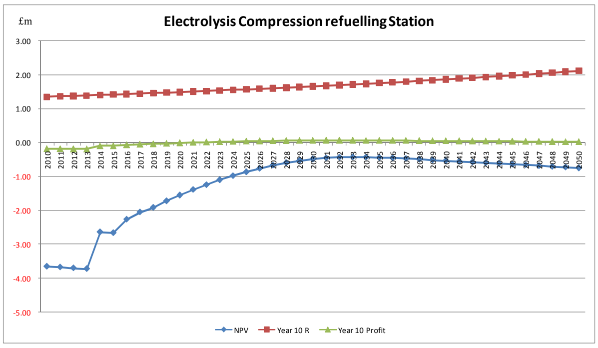



**Figure 4.5 NPV, Year 10 Profit and Year 10 Revenue for Small Scale REC**

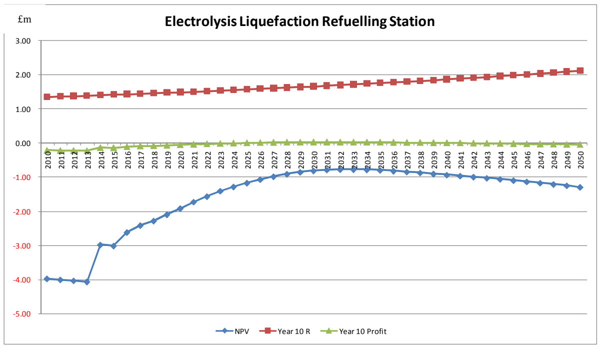



**Figure 4.6 NPV, Year 10 Profit and Year 10 Revenue for Small Scale REL**

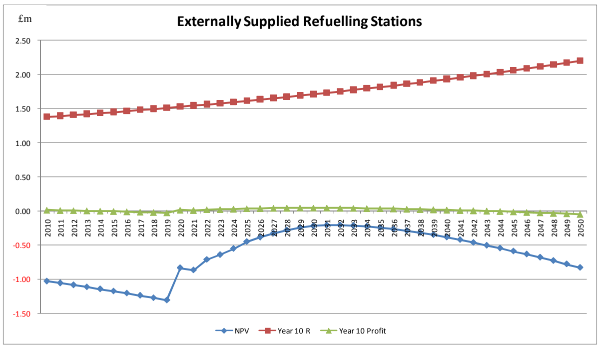



**Figure 4.7 NPV, Year 10 Profit and Year 10 Revenue for Small Scale Externally Supplied Refuelling Plant**

In contrast to the performance of the smaller units, when the larger class of units are considered rather better economics are evident. While the shapes of the curves shown in Figures 4.8 to 4.12 are not dissimilar to those representing the smaller plant, suggesting consistent temporal effects, the absolute levels are higher. Considering each aspect in turn, the year-10 revenues are higher reflecting the significantly higher output of these larger units and the same comments about revenue support as previously stated apply. These higher levels of revenues translate into improved profitability with year-10 margins being more consistently positive. Once again, margins are better for the electrolysis plant for the reasons explained earlier. The SMR compression plant achieves a positive NPV early in the analysis (2019) although the liquefied $H_2$ unit remains NPV negative throughout the analysis period. For the REL plant on the other hand, positive NPV appears achievable as early as 2014 and for the externally supplied plant from the outset, although there is an initial decline before NPVs rebound.

The superior performance of these larger units is largely explained by the relatively lower investment cost per unit of output assumed by the model. The relative cost is set to be lower since certain core elements would be scaled in direct proportion to the size of the unit, whilst others such as the balance of plant would not. This is consistent with the experience of current manufacturers of hydrogen production technology [152].

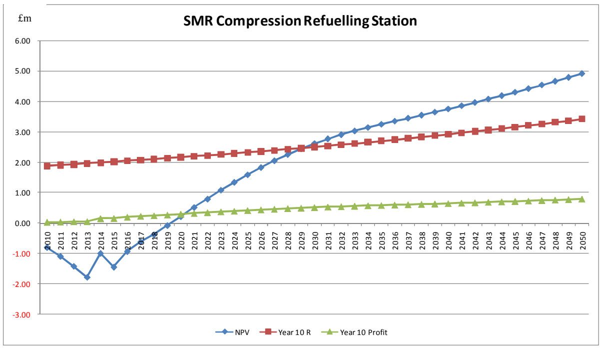



**Figure 4.8 NPV, Year 10 Profit and Year 10 Revenue for Large Scale RNGC**

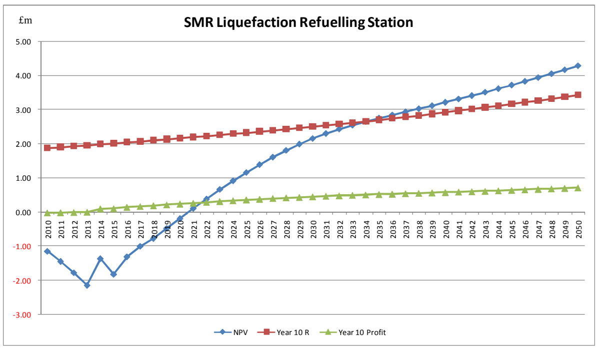



**Figure 4.9 NPV, Year 10 Profit and Year 10 Revenue for Large Scale RNGL**

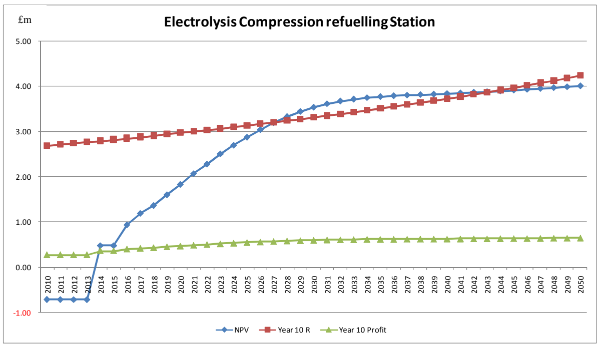



**Figure 4.10 NPV, Year 10 Profit and Year 10 Revenue for Large Scale REC**

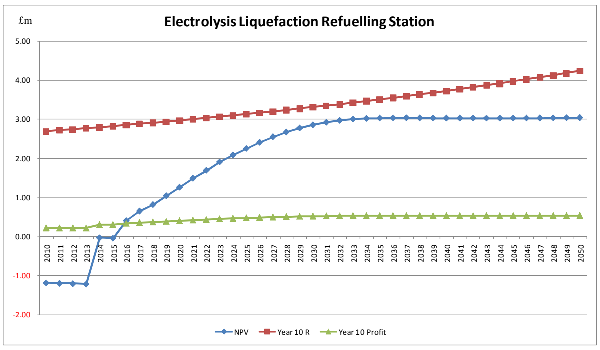



**Figure 4.11 NPV, Year 10 Profit and Year 10 Revenue for Large Scale REL**

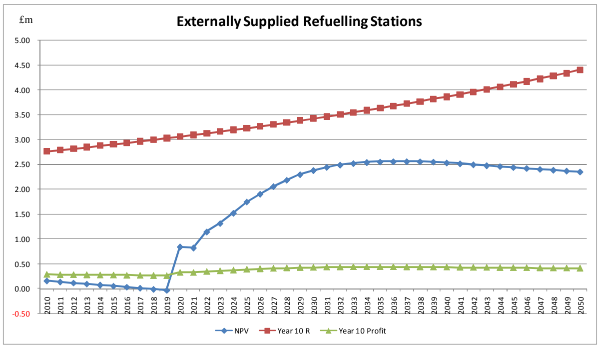



**Figure 4.12 NPV, Year 10 Profit and Year 10 Revenue for Large Scale Externally Supplied Refuelling Plant**

#### 4.2.1.2 Smaller-Scale Multi-Purpose Plant

The Micro-Scale Multi-Purpose plant demonstrate broadly similar economics to those demonstrated by the small scale refuelling units, as shown in Figures 4.13 to 4.16. Profitability is consistently negative as is the NPV while revenues demonstrate the roughly linear increase over time observed previously. Overall the NPV of the Micro-Scale units is more highly negative (on a pro-rata basis) than for the refuelling units which can be explained by the fact that the investment cost for these plant has been assumed to be relatively higher per unit of output [152].

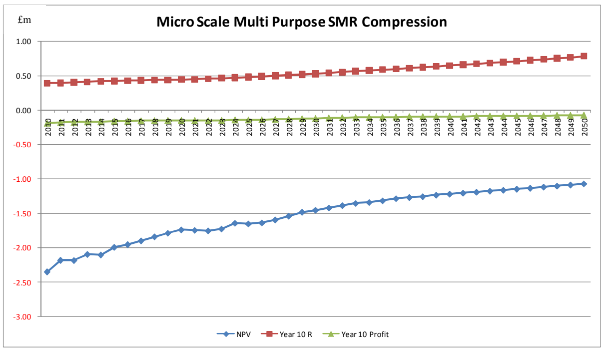



**Figure 4.13 NPV, Year 10 Profit and Year 10 Revenue for Micro Scale MNGC**

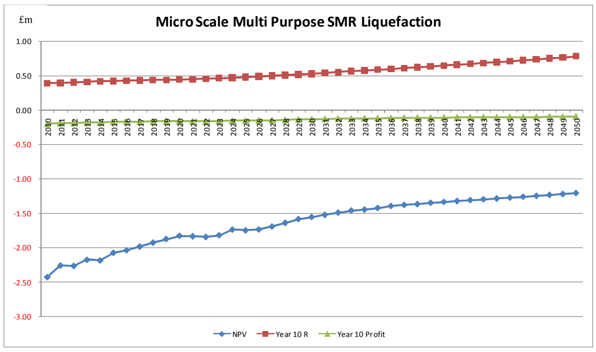
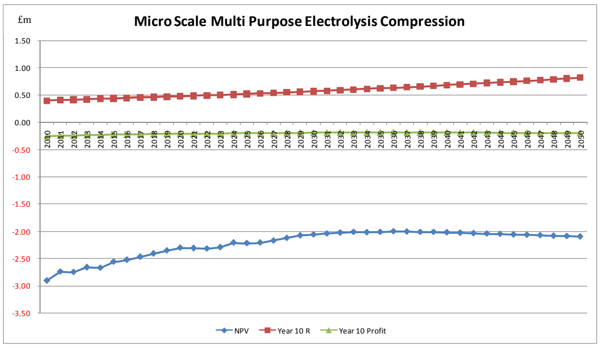



**Figure 4.14 NPV, Year 10 Profit and Year 10 Revenue for Micro Scale MNGL**



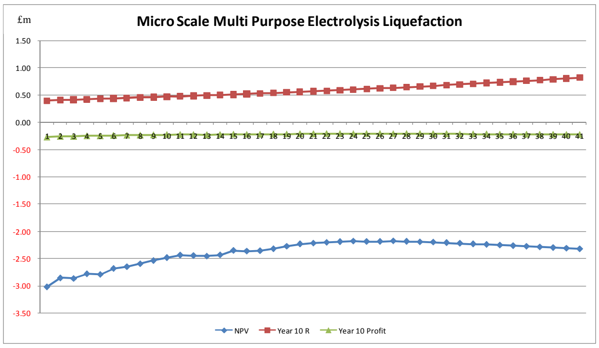
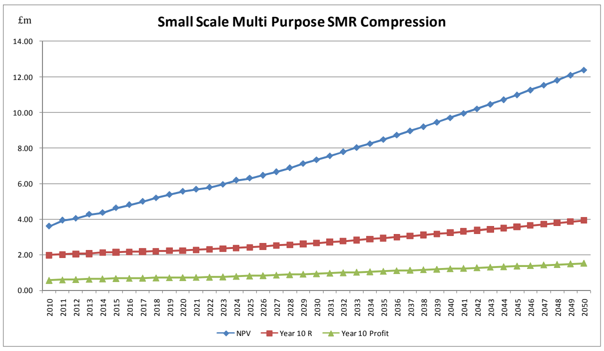




**Figure 4.15 NPV, Year 10 Profit and Year 10 Revenue for Micro Scale MEC**

**Figure 4.16 NPV, Year 10 Profit and Year 10 Revenue for Micro Scale MEL**

The Small Scale Multi-Purpose units (Figures 4.17 to 4.20) demonstrate significantly better performance than both the smaller versions and the refuelling plant discussed in Section 4.2.1.1. Margins are consistently positive over the period modelled and almost all the plant is shown to be NPV positive across the complete period too. Indeed, the NPV shows a monotonically increasing value over time as do the revenue and profit figures. The improved NPVs when compared with the similarly sized refuelling plant can be put down to the earlier and more rapid roll out of units in the model and hence a faster move down the learning curve. To put it another way, the plant performance is not normalised for capacity build up but reflects the speed of capacity expansion in the model.



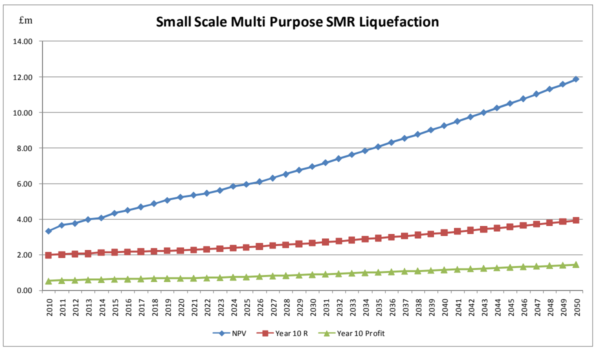
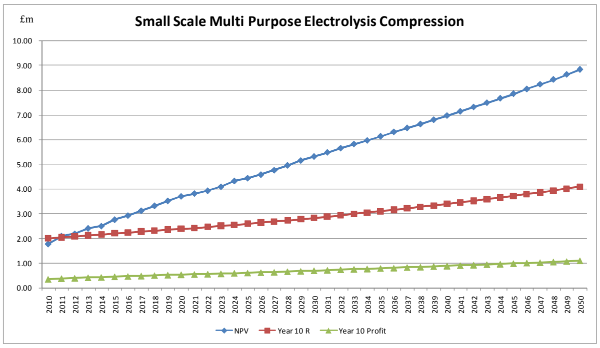




**Figure 4.17 NPV, Year 10 Profit and Year 10 Revenue for Small Scale MNGC**

**Figure 4.18 NPV, Year 10 Profit and Year 10 Revenue for Small Scale MNGL**



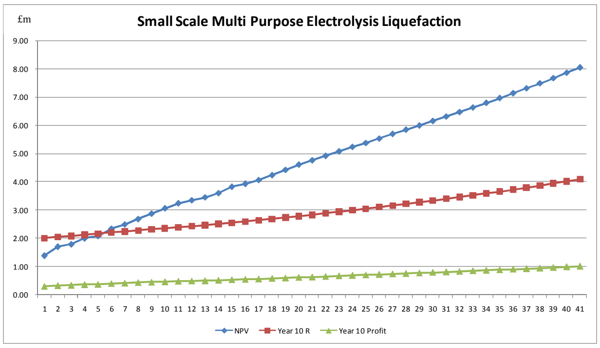




**Figure 4.19 NPV, Year 10 Profit and Year 10 Revenue for Small Scale MEC**

**Figure 4.20 NPV, Year 10 Profit and Year 10 Revenue for Small Scale MEL**

#### 4.2.1.3 Larger-Scale Multi-Purpose Plant

In general, the larger scale multi-purpose units demonstrate the most favourable economics of all the plant under consideration although this is not necessarily true across the whole period under consideration as can be seen from the charts in Figures 4.21 to 4.28. The units, both Mid-Scale and Large-Scale, all demonstrate positive margins throughout the analysis period with the usual comments applying to the relative revenue performance. In most instances across the period to 2050 the NPVs are positive and generally larger in absolute size compared with the other plant being considered. This would suggest that these larger plant are the more attractive investment proposition but the result should be treated with some caution. It is a matter of fact that the larger the NPV the more value a given project adds and NPV, as Benouna et al point out [117], is the preferred method of project evaluation, particularly in comparison to internal rate of return. If the NPV can be arrived at with certainty then the value of the company making the investment can always be maximised by choosing to invest in the highest NPV project it is able to for the level of investment funds it has available. However, where uncertainty exists (and it may reasonably be assumed that uncertainty will always exist) it may be, for example, that a project having a lower NPV but a higher degree of certainty would be preferred. Of course, it would be perfectly possible to take this relatively greater uncertainty into account in the discount rate or the sensitivity analysis carried out with respect to cashflows but a more risk averse investor may still prefer the smaller project on the basis that it does not "put all its eggs in one basket".

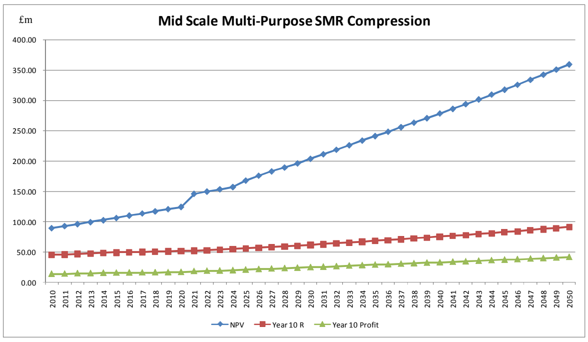



Figure 4.21 NPV, Year 10 Profit and Year 10 Revenue for Mid Scale MNGC

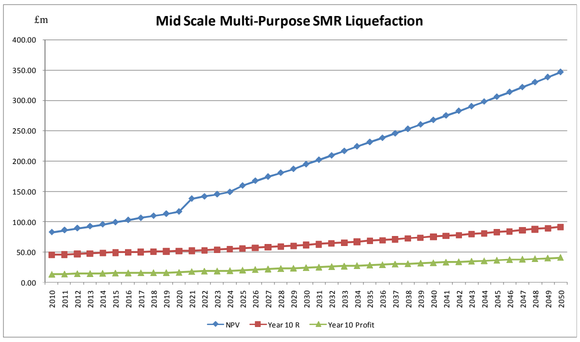



Figure 4.22 NPV, Year 10 Profit and Year 10 Revenue for Mid Scale MNGL

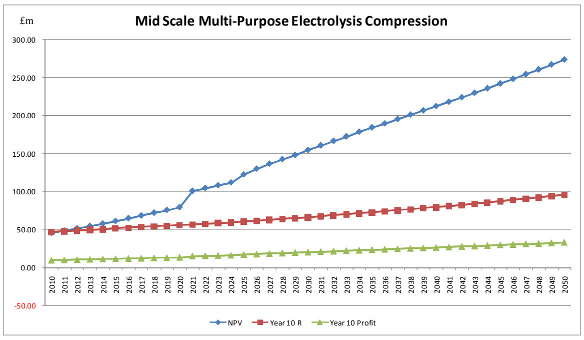



Figure 4.23 NPV, Year 10 Profit and Year 10 Revenue for Mid Scale MEC

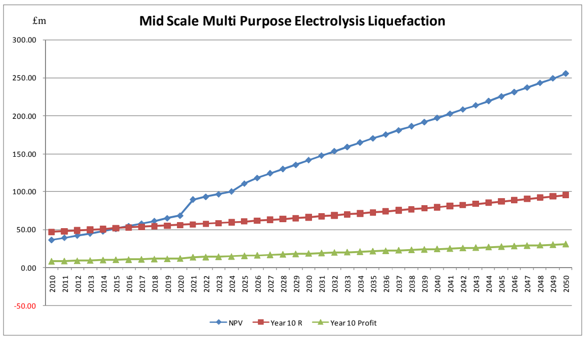



Figure 4.24 NPV, Year 10 Profit and Year 10 Revenue for Mid Scale MEL

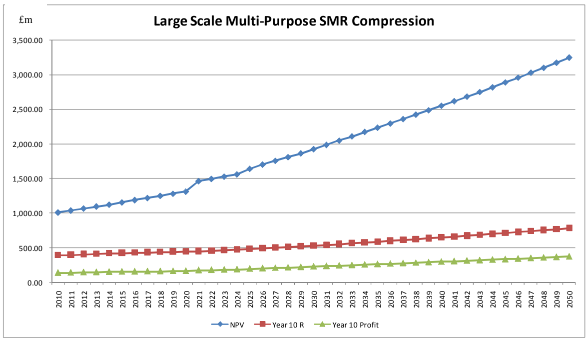



Figure 4.25 NPV, Year 10 Profit and Year 10 Revenue for Large Scale MNGC

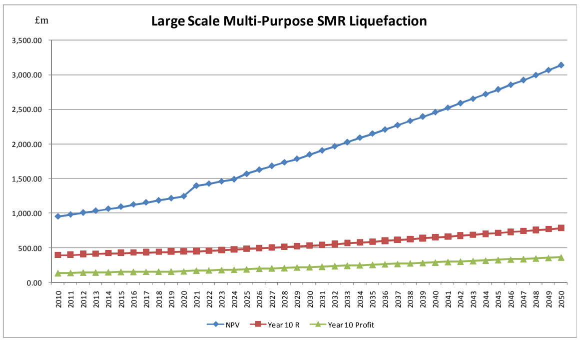
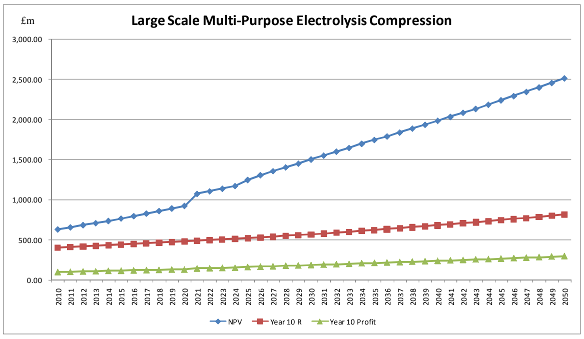



Figure 4.26 NPV, Year 10 Profit and Year 10 Revenue for Large Scale MNGL



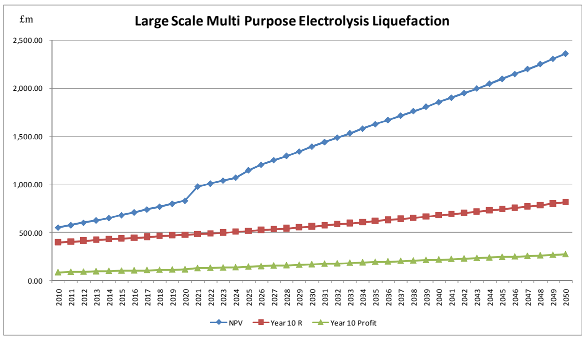




**Figure 4.27 NPV, Year 10 Profit and Year 10 Revenue for Large Scale MEC**

**Figure 4.28 NPV, Year 10 Profit and Year 10 Revenue for Large Scale MEL**

### 4.2.1 Sensitivity Analysis

The input variables and ranges that have been explored as part of the sensitivity analysis are provided in Table 4.3. This was carried out in part to better assess the functioning of the model but was also designed to identify the real effect these input parameters might have on future outcomes. These input parameters were selected based on two criteria; the first being whether they are known to have a significant impact on the model and second whether they have a specific intrinsic interest in terms of the study being undertaken. The sensitivity analysis is also used to inform the scenario analysis built around key input variables. Each of the sensitivity variables is assigned 5 possible values across the range and a probability has been assigned to each of the possible values in order to facilitate the calculation of a single output value across a range of possible input variables as discussed in Section 4.1.3. The sensitivities are then calculated in each of 3 reference years, namely 2015, 2025 and 2035.

By way of example, the relative sensitivity of the financial characteristics of the smaller natural gas and electrolysis plants (i.e. small refuelling units, micro multi-purpose units and mid-size multi-purpose units) to the seven input variables is presented in Figures 4.29 and 4.30 respectively; charts for the larger scale plant have been drawn but are not replicated here as they are quite similar. The charts present the median sensitivity indicators across the plant variants, relating each of the input variables to each of the three key outputs (NPV, year-10 revenue and year-10 profit) in each of the reference years.

| Parameter | Range | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Low-Low | Prob. (%) | Low | Prob. (%) | Base | Prob. (%) | High | Prob. (%) | High-High | Prob. (%) |
| **Macro-Economic Factors** | | | | | | | | | | |
| *Energy Price Inflation (%)* | 1.0 | 20.0 | NA | NA | 2.0 | 60.0 | NA | NA | 3.0 | 20.0 |
| **Fuel Prices** | | | | | | | | | | |
| *Transport Fuel Price (p/ litre PE)* | 80.0 | 5.0 | 90.0 | 10.0 | 100.0 | 30.0 | 130.0 | 40.0 | 180.0 | 15.0 |
| *Electricity Price (p/kWh)* | 1.5 | 5.0 | 2.0 | 10.0 | 2.5 | 30.0 | 4.5 | 40.0 | 6.5 | 15.0 |
| *Natural Gas (p/kWh)* | 0.5 | 5.0 | 1.0 | 10.0 | 1.5 | 30.0 | 2.0 | 40.0 | 3.5 | 15.0 |
| **Investment Costs** | | | | | | | | | | |
| *H2 Plant* | -40% | 20.0 | -20% | 20.0 | Base[a] | 20.0 | +20% | 20.0 | +40% | 20.0 |
| *Electricity Plant* | -40% | 20.0 | -20% | 20.0 | Base[a] | 20.0 | +20% | 20.0 | +40% | 20.0 |
| **Learning Coefficients** | | | | | | | | | | |
| *H2 plant (%)* | 5.0 | 20.0 | 7.5 | 20.0 | 10.0 | 20.0 | 12.5 | 20.0 | 15.0 | 20.0 |
| *Renewable plant (%)* | 5.0 | 20.0 | 7.5 | 20.0 | 10.0 | 20.0 | 12.5 | 20.0 | 15.0 | 20.0 |
| **Cost of Capital** | | | | | | | | | | |
| *Cost of Equity (%)* | 8.0 | 10.0 | 12.0 | 20.0 | 16.0 | 40.0 | 20.0 | 20.0 | 24.0 | 10.0 |
| **Policy / Market Instruments** | | | | | | | | | | |
| *ROC (£ / MWh)* | 15.0 | 5.0 | 25.0 | 20.0 | 35.0 | 30.0 | 45.0 | 25.0 | 55.0 | 20.0 |
| *RTFO + Duty Benefit (p / litre PE)* | 0.0 | 5.0 | 20.0 | 20.0 | 35.0 | 30.0 | 45.0 | 25.0 | 55.0 | 20.0 |
| *Carbon Price (Euro Cent / kg)* | 0.4 | 10.0 | 0.8 | 15.0 | 1.2 | 20.0 | 1.6 | 35.0 | 2.0 | 20.0 |
| **Other** | | | | | | | | | | |
| *Effective Tax Rate (%)* | | | | | | | | | | |
| *Proportion Equity (%)* | | | | | | | | | | |

a. In each case the base case value corresponding to the given plant

**Table 4.3 Parameters and Ranges Explored in Sensitivity Analyses**

It is apparent that the variable to which the plant is most sensitive is the petrol price upon which the price of transport fuels is based. The performance of all plant types is significantly affected and there is a similar impact across all the output measures and in all reference years. Also of importance to all plant types is the TOC price plus duty benefit which is treated here as a supplementary price payable per litre of petrol equivalent and, therefore, directly affects the overall price being received by the producer in much the same way as the underlying petrol price although the impact is smaller. It should be noted that the price utilised in the model is the TOC buyout price since at present the TOC price stands below this figure suggesting that all companies expect to achieve their targets. Similarly the investment cost has a significant impact on all plant types but only affects the profits and the NPV and not the revenues. While the petrol price displays a positive correlation between input and output, the investment cost has a negative correlation as would be expected. The NPV is directly influenced by the choice of investment cost whereas the profitability is indirectly affected through the financing structure; since the investments are assumed to be partially funded by debt, the interest burden increases as the size of investment increases and hence the profitability decreases. Interestingly, both the natural gas and electrolysis plant are impacted by changes to the price of natural gas since in both cases the revenue generated by the multi-purpose plant is a function of the price of gas. In the case of the natural gas plant, the profitability is affected by the cost of natural gas as well which explains the negative correlation between this value and the gas price. In similar vein, the NPV of natural gas plant is negatively impacted by increasing gas prices while the electrolysis units are positively affected.

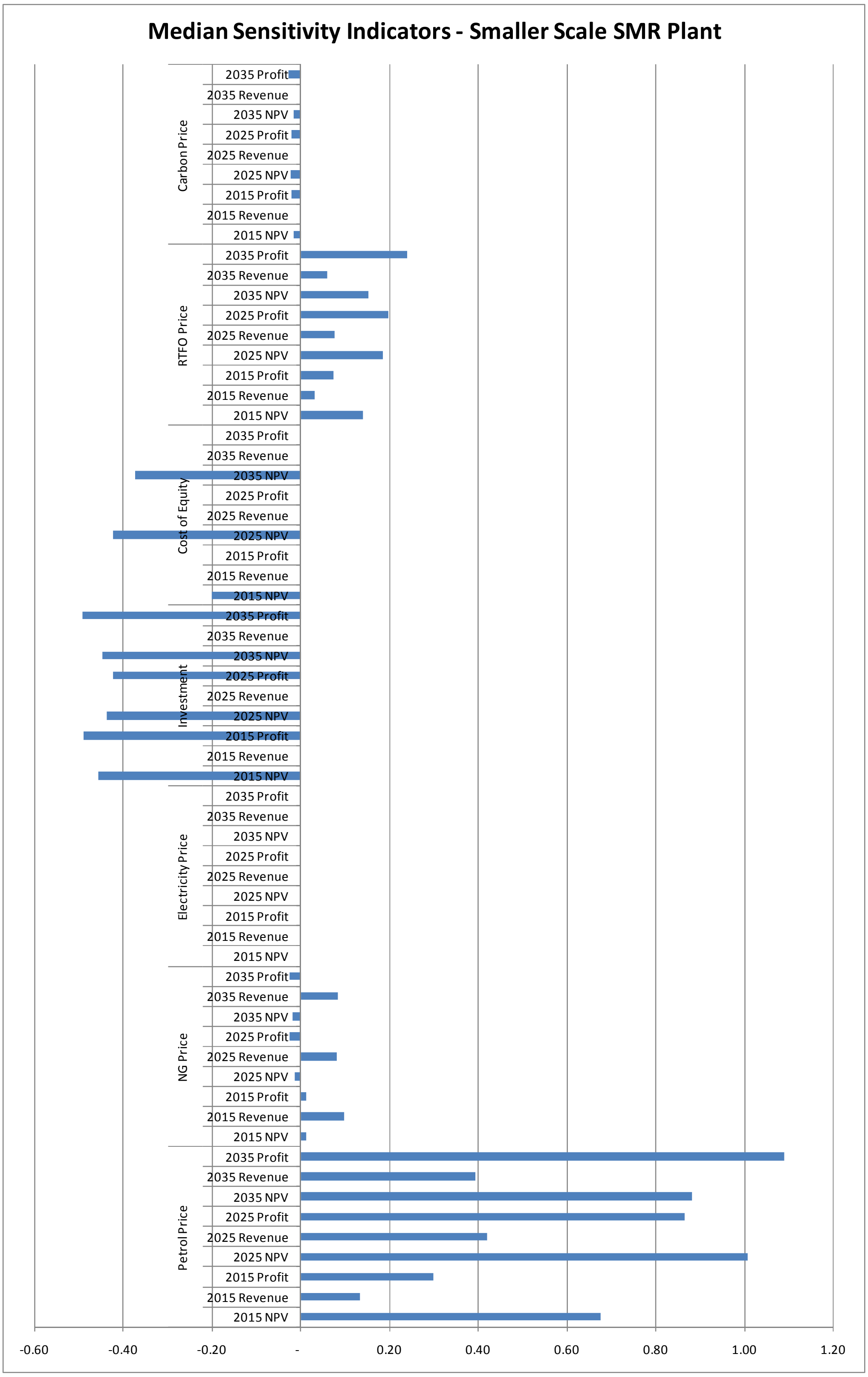



**Figure 4.29 Median Sensitivity Indicators for SMR Plant**

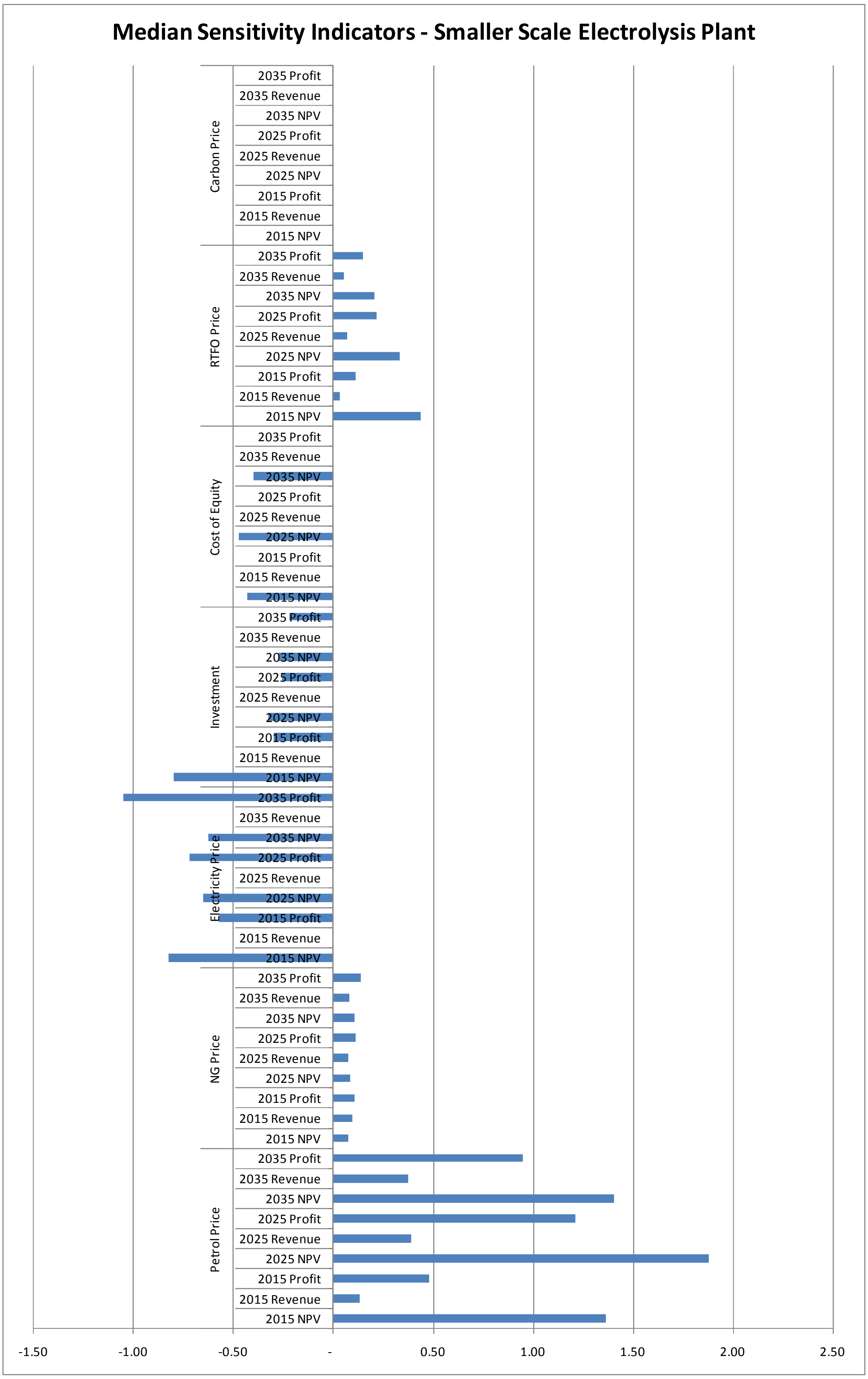



**Figure 4.30 Median Sensitivity Indicators for Electrolysis Plant**

Where the natural gas and electrolysis plant types demonstrate divergent sensitivity behaviour is in terms of the influence of carbon price and electricity price. Since the electrolysis plant is assumed to be supplied by low carbon electricity the output is unaffected by the variation in carbon price. By contrast, the carbon price does affect the natural gas units negatively although the sensitivity is relatively small. Once again, only the profitability and NPV are influenced by changes to the carbon price as this is introduced as a cost in the model. Conversely, natural gas plant are unaffected by the price of electricity while, unsurprisingly, this is an important input to the profitability and NPV of the electrolysis units since this represents a significant proportion of the total input costs. The correlation of the electrolysis plant to the price of electricity is once again negative.

While in general terms the magnitude of the sensitivity indicator varies relatively little over time there is a certain degree of variability demonstrated between different plant types which is why the median values were selected. Tables 4.4 and 4.5 present the median, maximum and minimum sensitivity indicator values across the complete range of plant types for each of the seven input parameters. The variability observed reflects the particularities of each plant type but overall these remain within reasonably tight bounds and demonstrate the same sense (either positive or negative) across the range except in a few special circumstances. The outlying values (for example, NPV 2015 sensitivity to petrol price) can be explained by the presence of a zero crossing in the results which leads to the denominator of either the output or input being very small in magnitude.

| | | NPV 2015 | Yr 10 R 2015 | Yr10π 2015 | NPV 2025 | Yr 10 R 2025 | Yr10π 2025 | NPV 2035 | Yr 10 R 2035 | Yr10π 2035 |
|---|---|---|---|---|---|---|---|---|---|---|
| Petrol Price | Median | 0.67 | 0.13 | 0.30 | 1.00 | 0.42 | 0.86 | 0.88 | 0.39 | 1.09 |
| | Max | 1.22 | 3.03 | 2.00 | 1.93 | 3.35 | 2.89 | 2.45 | 3.66 | 3.42 |
| | Min | 0.14 | 0.13 | 0.28 | 0.48 | 0.42 | 0.81 | 0.70 | 0.39 | 0.65 |
| Natural Gas Price | Median | 0.01 | 0.10 | 0.01 | -0.01 | 0.08 | -0.03 | -0.02 | 0.08 | -0.03 |
| | Max | 0.21 | 0.10 | 1.71 | 0.75 | 0.08 | 0.94 | 53.37 | 0.08 | 0.59 |
| | Min | 0.01 | - | 0.01 | 0.00 | - | 0.00 | 0.00 | - | 0.00 |
| Electricity Price | Median | - | - | - | - | - | - | - | - | - |
| | Max | - | - | - | - | - | - | - | - | - |
| | Min | - | - | - | - | - | - | - | - | - |
| Investment | Median | -0.46 | - | -0.49 | -0.44 | - | -0.42 | -0.45 | - | -0.49 |
| | Max | 0.77 | - | 1.96 | 1.23 | - | 5.21 | 2.62 | - | 0.96 |
| | Min | 0.41 | - | 0.15 | 0.22 | - | 0.09 | 0.12 | - | 0.06 |
| Cost of Equity | Median | -0.20 | - | - | -0.42 | - | - | -0.37 | - | - |
| | Max | 0.53 | - | - | 0.83 | - | - | 8.00 | - | - |
| | Min | 0.01 | - | - | 0.00 | - | - | 0.02 | - | - |
| RTFO Price | Median | 0.14 | 0.03 | 0.07 | 0.18 | 0.08 | 0.20 | 0.15 | 0.06 | 0.24 |
| | Max | 0.40 | 0.57 | 0.68 | 0.58 | 0.47 | 1.02 | 0.73 | 0.38 | 1.39 |
| | Min | 0.04 | 0.03 | 0.07 | 0.11 | 0.08 | 0.15 | 0.13 | 0.06 | 0.10 |
| Carbon Price | Median | -0.02 | - | -0.02 | -0.02 | - | -0.02 | -0.02 | - | -0.03 |
| | Max | 0.05 | - | 0.04 | 0.04 | - | 1.37 | 0.07 | - | 0.31 |
| | Min | 0.01 | - | 0.02 | 0.01 | - | 0.02 | 0.01 | - | 0.01 |

**Table 4.4 Variability of Sensitivity Indicators Across Range of SMR Plant Types**

| | | NPV 2015 | Yr 10 R 2015 | Yr10π 2015 | NPV 2025 | Yr 10 R 2025 | Yr10π 2025 | NPV 2035 | Yr 10 R 2035 | Yr10π 2035 |
|---|---|---|---|---|---|---|---|---|---|---|
| Petrol Price | Median | 1.36 | 0.13 | 0.48 | 1.88 | 0.39 | 1.21 | 1.40 | 0.37 | 0.95 |
| | Max | 82.91 | 1.78 | 2.42 | 2.21 | 2.05 | 3.26 | 2.50 | 2.33 | 3.37 |
| | Min | 0.12 | 0.13 | 0.20 | 0.39 | 0.39 | 0.64 | 0.57 | 0.37 | 0.75 |
| Natural Gas Price | Median | 0.08 | 0.09 | 0.11 | 0.09 | 0.07 | 0.11 | 0.10 | 0.08 | 0.14 |
| | Max | 0.84 | 0.09 | 0.64 | 0.99 | 0.07 | 0.27 | 0.36 | 0.08 | 0.23 |
| | Min | - | - | - | - | - | - | - | - | - |
| Electricity Price | Median | -0.82 | - | -0.57 | -0.65 | - | -0.72 | -0.62 | - | -1.05 |
| | Max | 1.47 | - | 10.59 | 5.08 | - | 2.21 | 62.19 | - | 2.04 |
| | Min | 0.28 | - | 0.49 | 0.43 | - | 0.42 | 0.44 | - | 0.36 |
| Investment | Median | -0.80 | - | -0.30 | -0.33 | - | -0.26 | -0.27 | - | -0.22 |
| | Max | 1.14 | - | 17.62 | 2.29 | - | 1.69 | 4.16 | - | 1.38 |
| | Min | 0.33 | - | 0.20 | 0.30 | - | 0.12 | 0.16 | - | 0.07 |
| Cost of Equity | Median | -0.43 | - | - | -0.47 | - | - | -0.40 | - | - |
| | Max | 0.69 | - | - | 2.79 | - | - | 217.85 | - | - |
| | Min | 0.06 | - | - | 0.08 | - | - | 0.10 | - | - |
| RTFO Price | Median | 0.44 | 0.03 | 0.11 | 0.33 | 0.07 | 0.21 | 0.20 | 0.06 | 0.15 |
| | Max | 3.05 | 0.36 | 0.84 | 0.65 | 0.32 | 1.23 | 0.76 | 0.28 | 1.36 |
| | Min | 0.03 | 0.03 | 0.05 | 0.08 | 0.07 | 0.14 | 0.11 | 0.06 | 0.13 |
| Carbon Price | Median | - | - | - | - | - | - | - | - | - |
| | Max | - | - | - | - | - | - | - | - | - |
| | Min | - | - | - | - | - | - | - | - | - |

**Table 4.5 Variability of Sensitivity Indicators Across Range of Electrolysis Plant Types**

### 4.2.2 Probability Weighted Analysis

Each set of plant types, i.e. refuelling stations, smaller scale multi-purpose and larger scale multi-purpose, is considered according to the probability weighted NPV, revenue and profitability in each of the reference years.

#### 4.2.2.1 Refuelling Plant

Figures 4.31 and 4.32 display the probability weighted NPV analysis described in Section 3.5.3.1 which shows that all plant types demonstrate improving NPV over time and a fairly close clustering of results. However, the NPVs of the smaller plant are all negative across the time period while the larger electrolysis plant variants all demonstrate positive NPVs in the later years. The NPV of natural gas supplied plant initially have lower NPV than their electrolysis based counterparts but in later years this situation reverses. This might seem counter-intuitive but can in part be explained by the fact that the same learning characteristics have been chosen for each type of plant. While electrolysis plant is relatively mature, the learning characteristics differ from SMR plant given the different nature of the technology which may be referred to as “surface area” and where cost is less closely linked to volume.

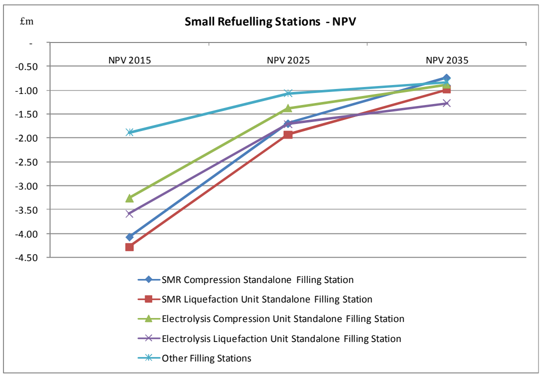



**Figure 4.31 NPV Probability Weighted Sensitivity Analysis Small Scale Refuelling Stations**

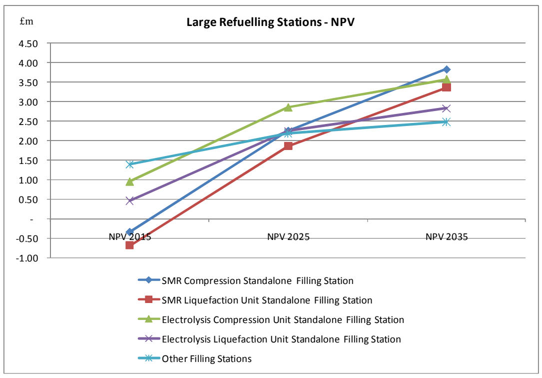
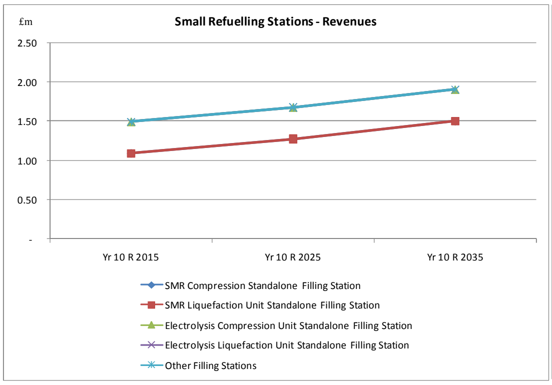
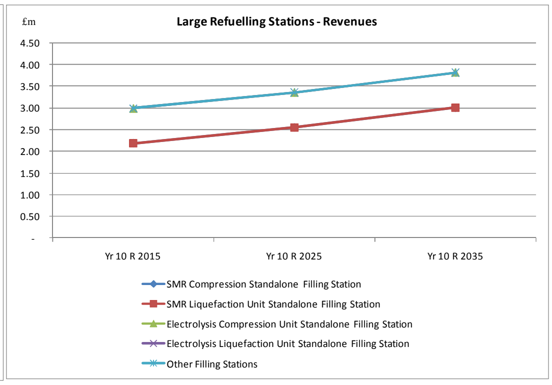



**Figure 4.32 NPV Probability Weighted Sensitivity Analysis Large Scale Refuelling Stations**

Figures 4.33 and 4.34 display the relative probability-weighted revenues. Consistent with the results in Section 4.2.1, there is a differential between the electrolysis-based plant and the natural gas based plant but within those categories very little difference is evident.



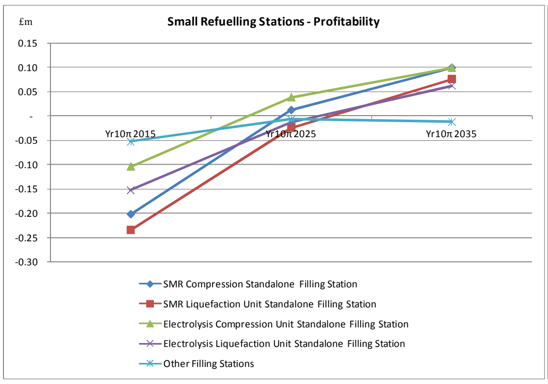




Note: Lines corresponding to the two NG and the other filling stations are overlaid as are the two electrolysis type plants

**Figure 4.33 Year 10 Revenues Probability Weighted Sensitivity Analysis Small Scale Refuelling Stations**

**Figure 4.34 Year 10 Revenues Probability Weighted Sensitivity Analysis Large Scale Refuelling Stations**

Figures 4.35 and 4.36 display the profitability results. In general the plant show evidence of increasing profitability over time although there is a flattening in later years and some tail off demonstrated by the electrolysis units. As described previously, this derives from the increasing impact of fuel costs relative to the increase in the price of the plant outputs.



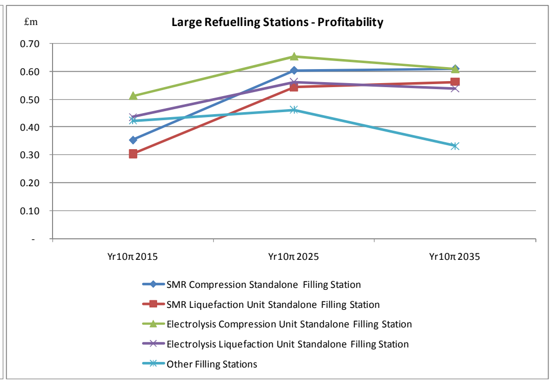




**Figure 4.35 Year 10 Profits Probability Weighted Sensitivity Analysis Small Scale Refuelling Stations**

**Figure 4.36 Year 10 Profits Probability Weighted Sensitivity Analysis Large Scale Refuelling Stations**

#### 4.2.2.2 Micro and Small Scale Multi-Purpose Units

In contrast to the refuelling stations described in the previous section, the NPV of the smaller scale multi-purpose units display a significant divergence between the SMR and electrolysis types. Furthermore the results do not show the same flattening over time as was present with the refuelling stations. This is in part the result of the closer correlation that exists in the model between the input energy and output energy prices since the hydrogen fuel produced is not only destined for the transport fuel market where the price differentials are higher. While the NPV of the micro versions are consistently negative, those of the small units are consistently positive, in line with the lower capital costs per unit of output for the larger units as shown in Figures 4.37 and 4.38.

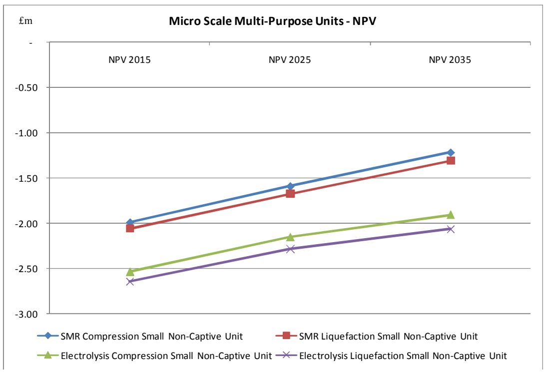



**Figure 4.37 NPV Probability Weighted Sensitivity Analysis Micro Scale Multi Purpose Units**

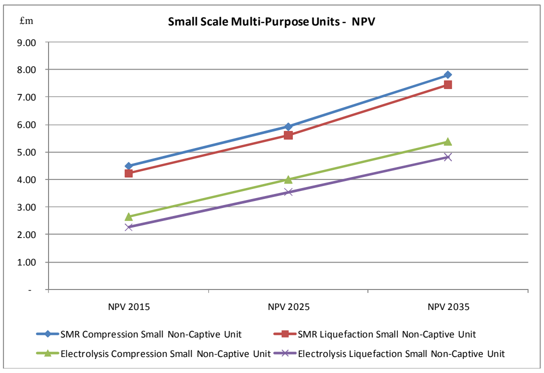
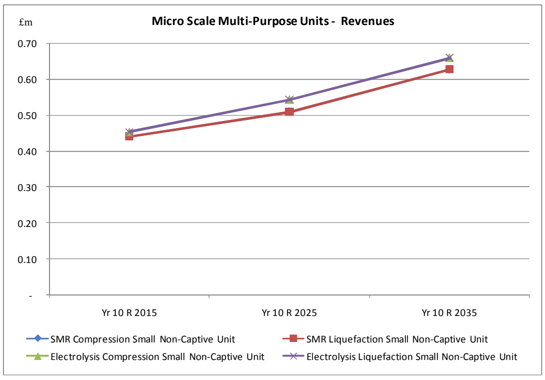
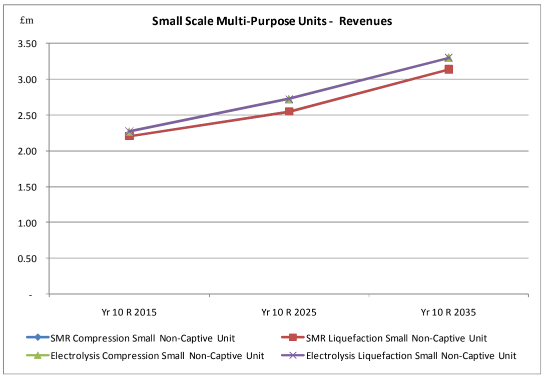



**Figure 4.38 NPV Probability Weighted Sensitivity Analysis Small Scale Multi Purpose Units**

The revenue results are broadly similar to those obtained for the refuelling stations except the revenues are smaller given the smaller size of the output as shown in Figures 4.39 and 4.40. Moreover, there is less divergence between the natural gas and electricity alternatives.



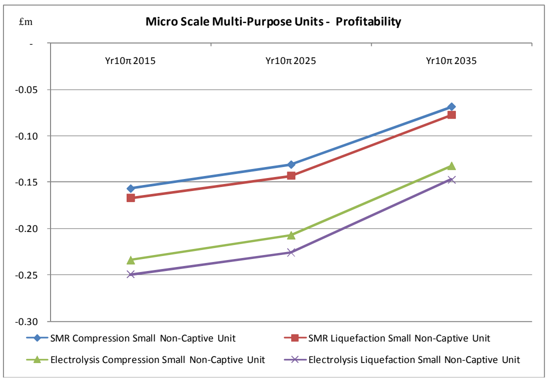




*Note: Lines corresponding to the two NG and the other filling stations are overlaid as are the two electrolysis type plants*

**Figure 4.39 Year 10 Revenues Probability Weighted Sensitivity Analysis Micro Scale Multi Purpose Units**

**Figure 4.40 Year 10 Revenues Probability Weighted Sensitivity Analysis Small Scale Multi Purpose Units**

The Micro Scale units remain unprofitable across the three reference years while the Small-Scale Units are consistently profitable as can be seen in Figures 4.41 and 4.42. While the Micro-Scale Units demonstrate an increasing improvement in profitability, the Small Scale units show the same flattening of profitability growth observed elsewhere. This simply reflects the specific economics of the different plant.



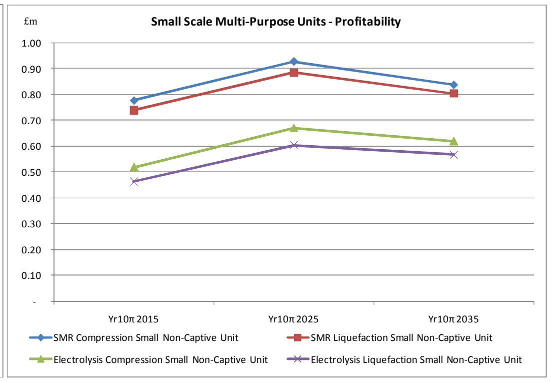




**Figure 4.41 Year 10 Profits Probability Weighted Sensitivity Analysis Micro Scale Multi Purpose Units**

**Figure 4.42 Year 10 Profits Probability Weighted Sensitivity Analysis Small Scale Multi Purpose Units**

#### 4.2.2.3 Mid and Large Scale Multi-Purpose Units

The Mid-Scale Multi-Purpose units show a sharply increasing NPV curve over time, while the Large-Scale units display a more modest relative rise as illustrated in Figures 4.43 and 4.44.

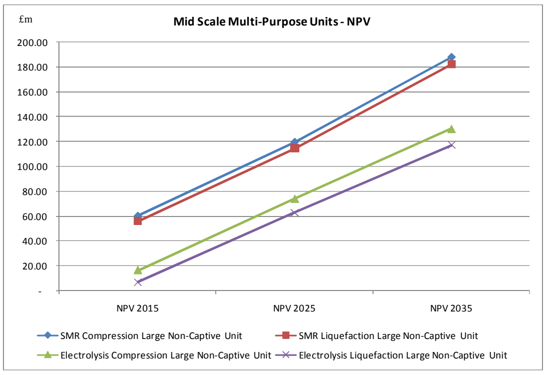



**Figure 4.43 NPV Probability Weighted Sensitivity Analysis Mid Scale Multi Purpose Units**

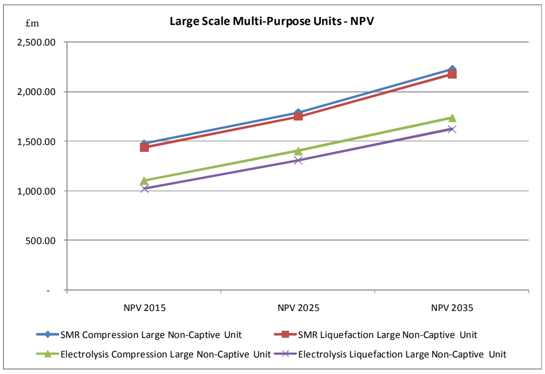



**Figure 4.44 NPV Probability Weighted Sensitivity Analysis Large Scale Multi Purpose Units**

Revenues follow a familiar pattern with relatively lower divergence between natural gas and electrolysis types as shown in Figures 4.45 and 4.46.

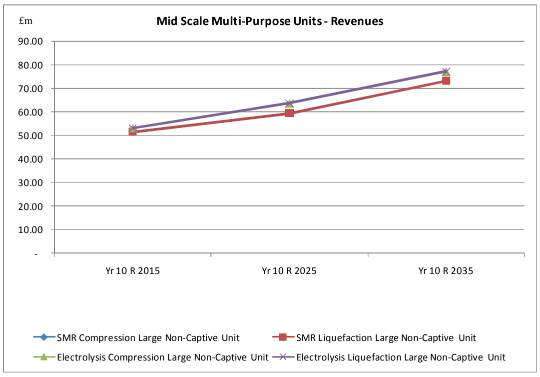



**Figure 4.45 Year 10 Revenues Probability Weighted Sensitivity Analysis Mid Scale Multi Purpose Units**

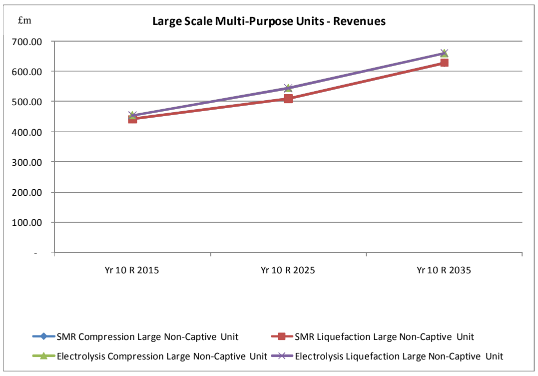



**Figure 4.46 Year 10 Revenues Probability Weighted Sensitivity Analysis Large Scale Multi Purpose Units**

Profits, as shown in Figures 4.47 and 4.48 flatten and indeed slightly decline in the later reference year for most plant in the same way as for the refuelling stations (see Figures 4.35 and 4.36).

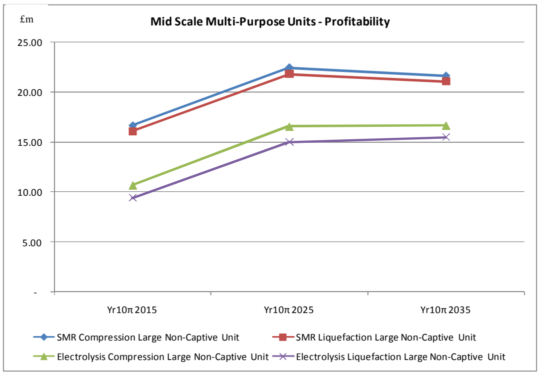



**Figure 4.47 Year 10 Profits Probability Weighted Sensitivity Analysis Mid Scale Multi Purpose Units**

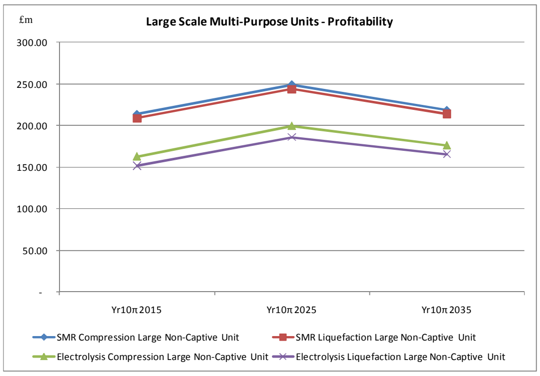



**Figure 4.48 Year 10 Profits Probability Weighted Sensitivity Analysis Large Scale Multi Purpose Units**

### 4.2.3 Scenario Analysis

Turning attention to the scenario analysis, the values attributed to each of the main input variables corresponding to the four scenarios described in Figure 4.2 and set out in Table 4.2. For the sake of computational simplicity and bearing in mind the limitations presented by Microsoft Excel, each is assumed to demonstrate a Normal Distribution and for each parameter the mean and standard deviation is defined in order to facilitate Monte Carlo simulations, with the means corresponding to the base case scenarios in the sensitivity analysis and the standard deviations being based on the observed historical variability of these input parameters.

Figures 4.49 to 4.54 present the results of the analyses for both the smaller and larger scale set of units according to the NPV, revenue and profit measures in the reference years and the scenarios described in Section 4.1.4. With regards to the refuelling stations (Figures 4.49 and 4.50), what immediately becomes apparent is the bifurcated nature of the results with the Business as Usual (BAU) and Unfavourable Markets (UMA) scenarios resulting in negative NPV and profitability profiles, while the Sustainability (SUS) and Favourable Markets (FMA) scenarios show positive results. Interestingly, the results from the FMA and SUS cases are quite similar suggesting that the impact of the policy measures is, in this case, lower than the impact of the market conditions. This is consistent with the sensitivity analysis which showed the largest impact on the outputs resulting from changes to the price of hydrogen (priced with reference to the price of the substitute fossil fuels).

With respect to the Micro Scale Multi Purpose Units (Figure 4.51) the NPV and profitability are negative almost entirely across the periods considered, although the UMA and BAU cases are clearly less favourable than the SUS and FMA cases. For Small Scale units (Figure 4.52), the clear bifurcation once again emerges with a split between negative NPV and profits for the unfavourable scenarios and positive for the favourable scenarios. This pattern continues for the Mid Scale (Figure 4.53) and Large Scale units (Figure 4.54). In terms of temporal effects, this is consistent with the results obtained from the base case sensitivity and probability-weighted sensitivity analysis.

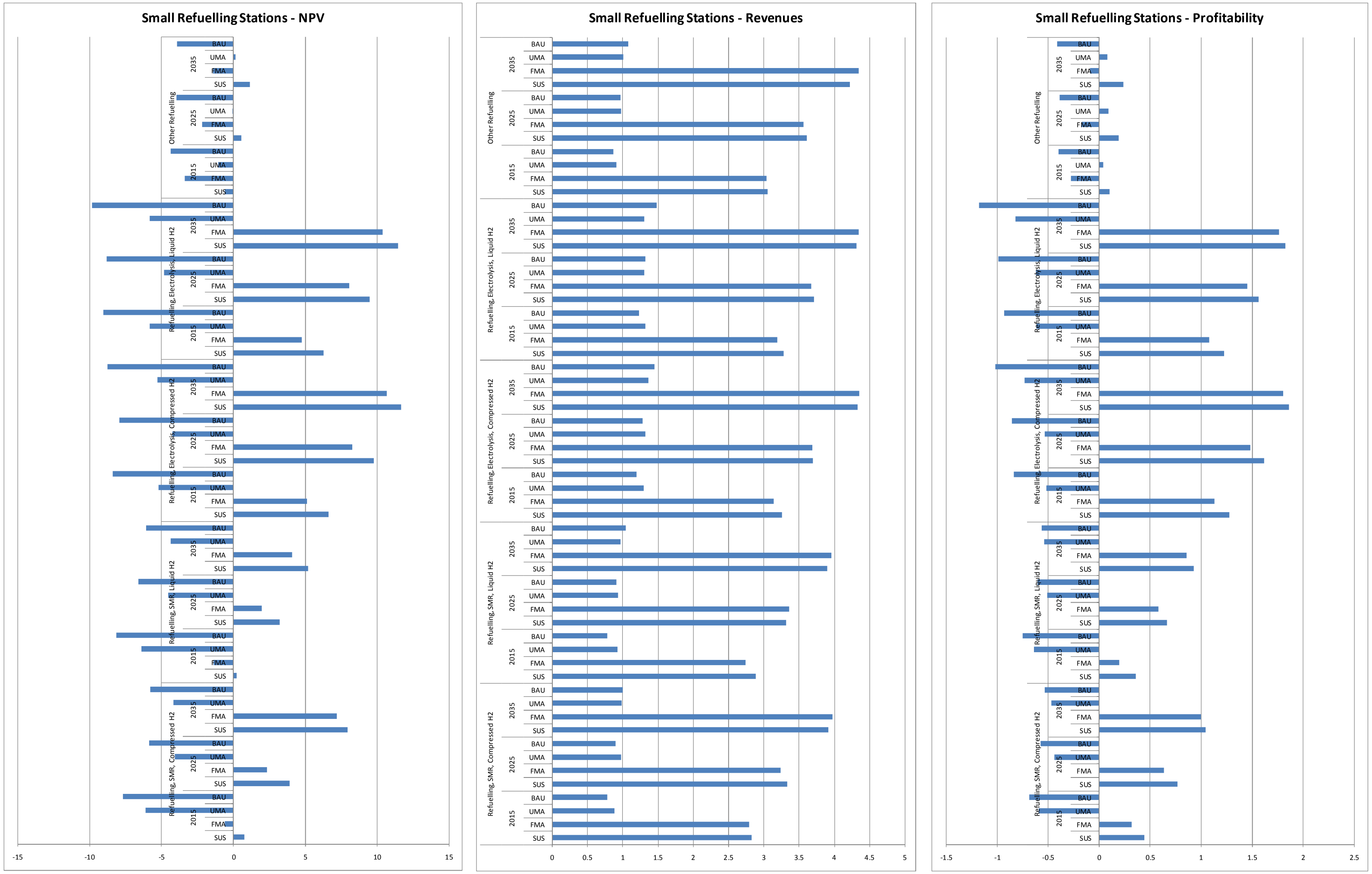



Figure 4.49 Results of Monte Carlo Scenario Simulation for Small Refuelling Stations

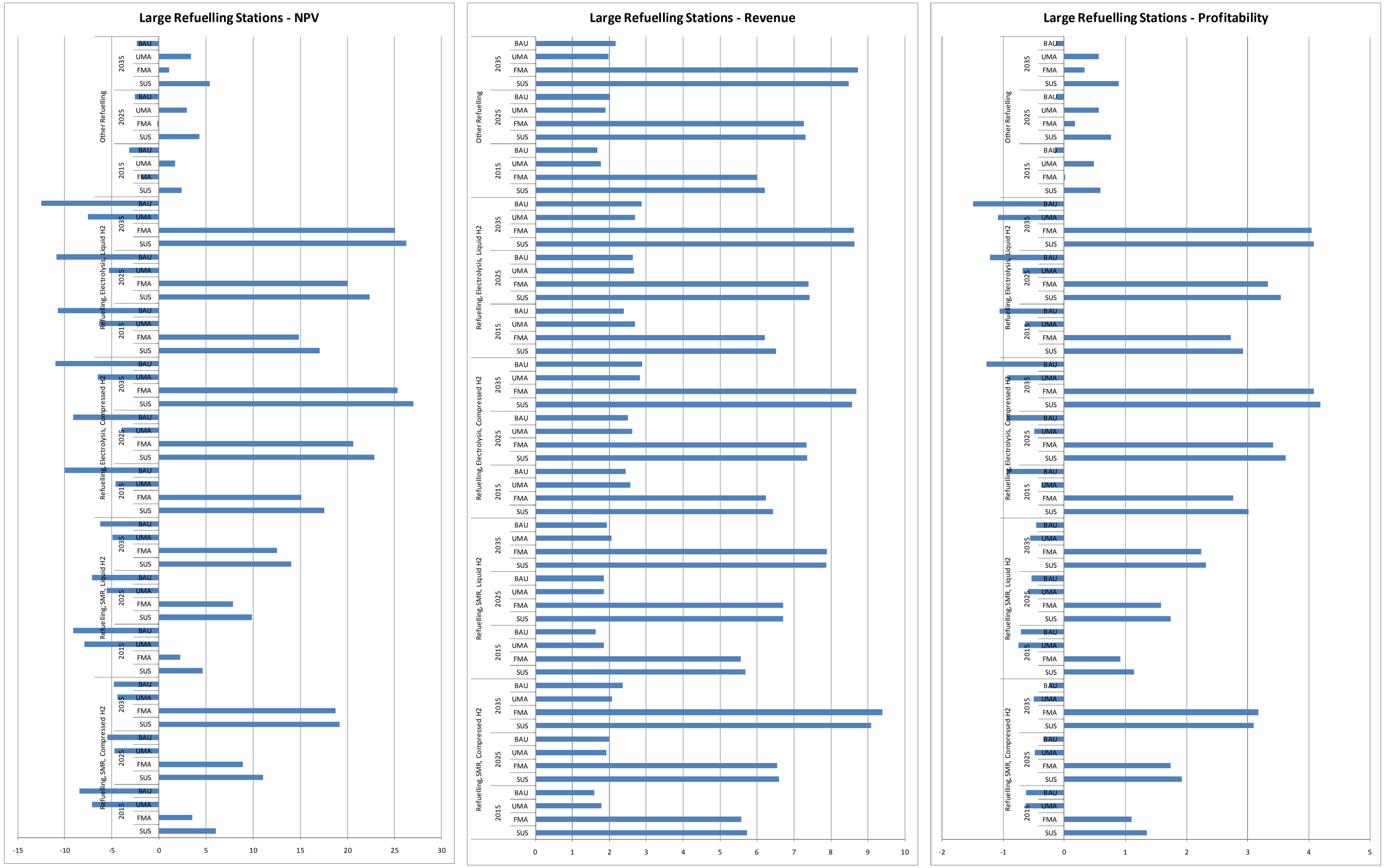



Figure 4.50 Results of Monte Carlo Scenario Simulation for Large Refuelling Stations

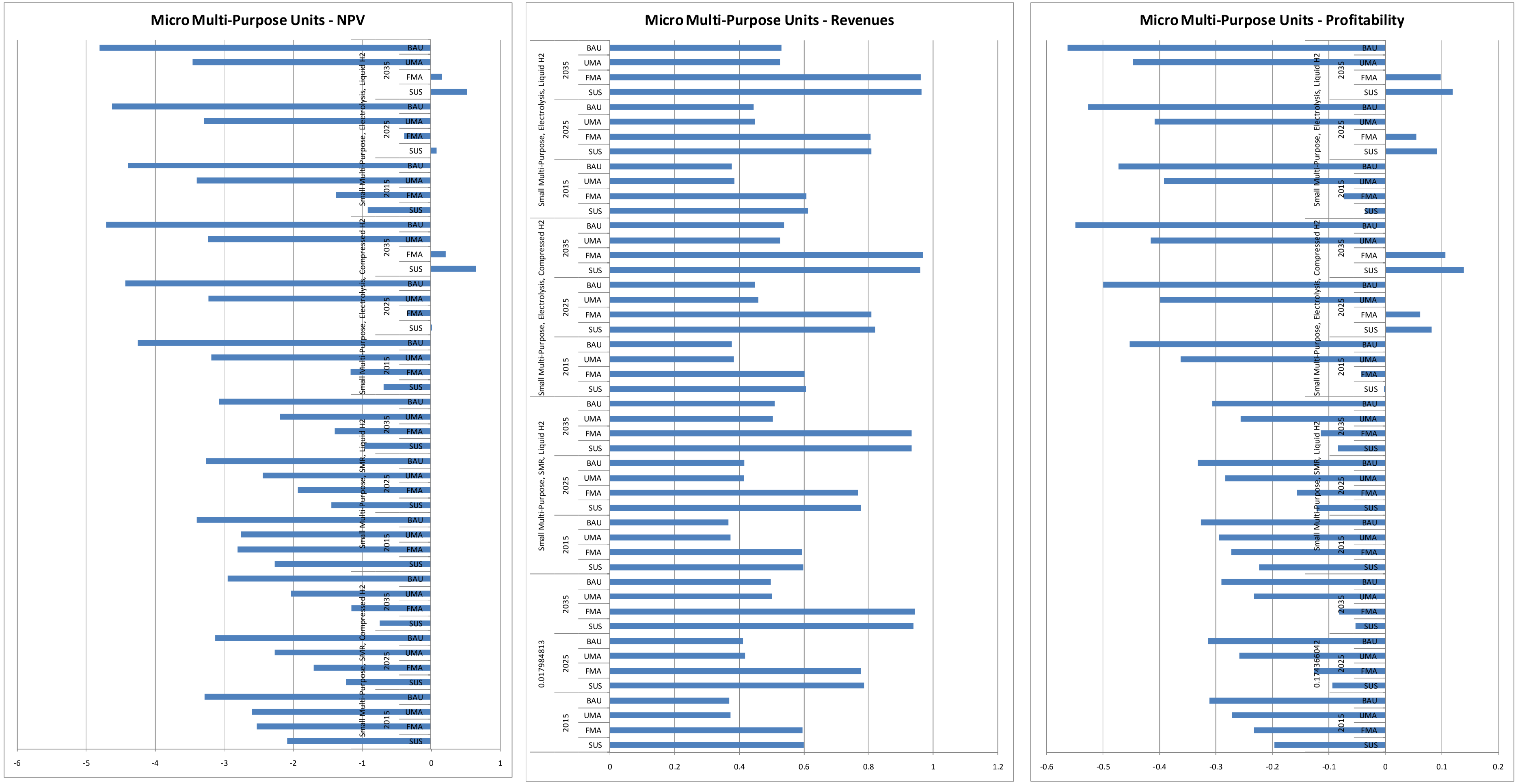



Figure 4.51 Results of Monte Carlo Scenario Simulation for Micro Scale Multi-Purpose Hydrogen Production Units

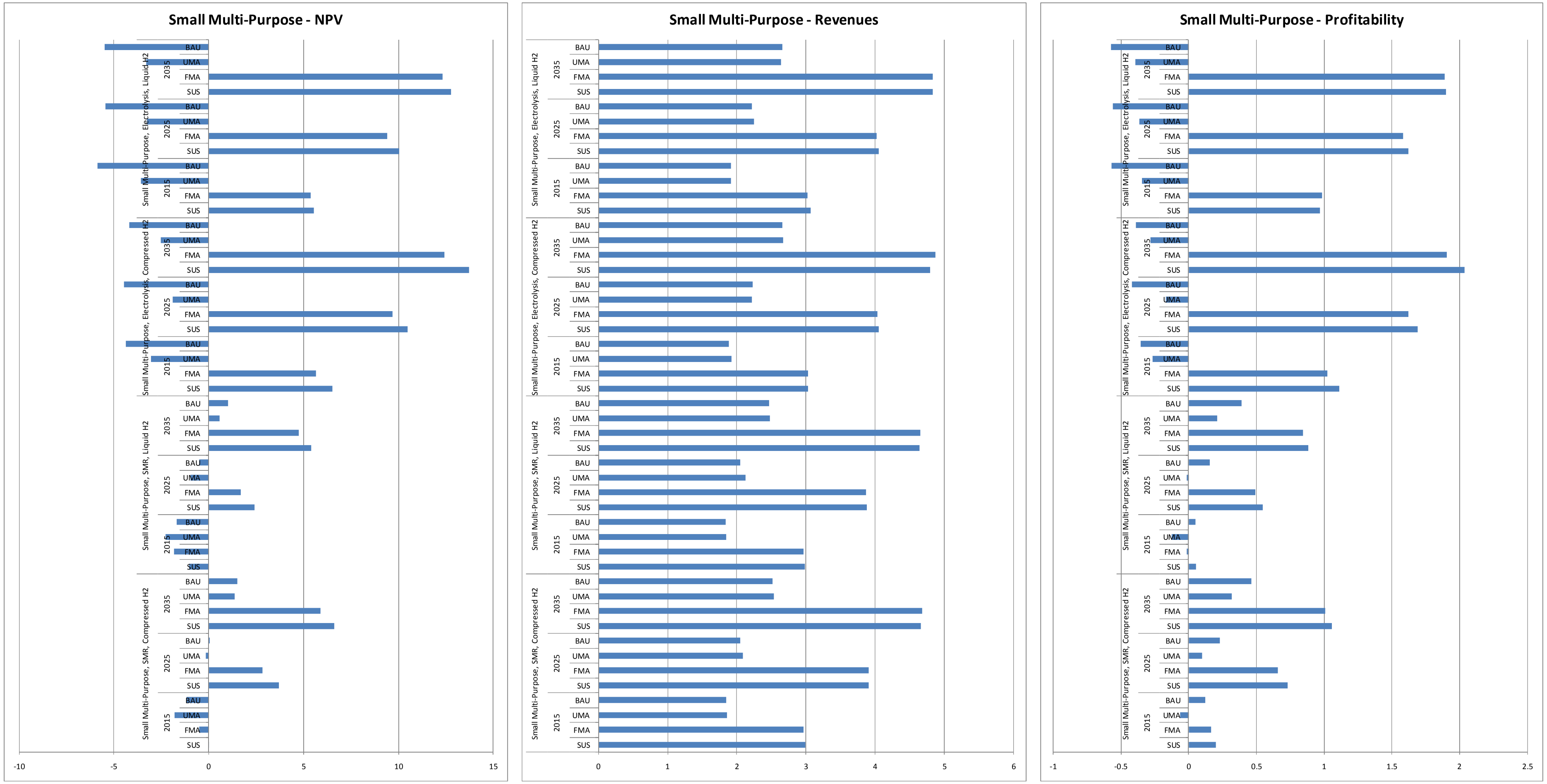



Figure 4.52 Results of Monte Carlo Scenario Simulation for Small Scale Multi-Purpose Hydrogen Production Units

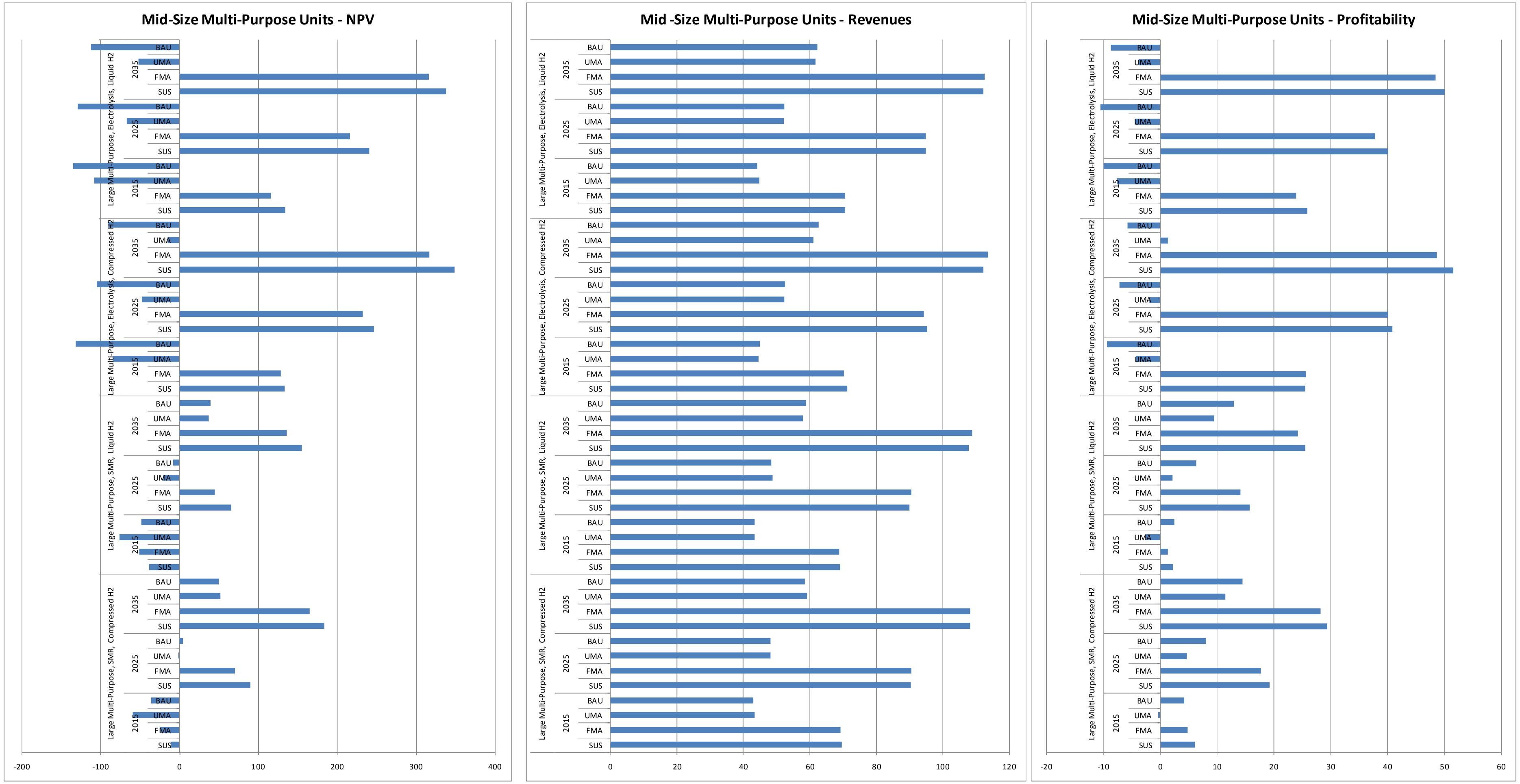



**Figure 4.53 Results of Monte Carlo Scenario Simulation for Mid Scale Multi-Purpose Hydrogen Production Units**

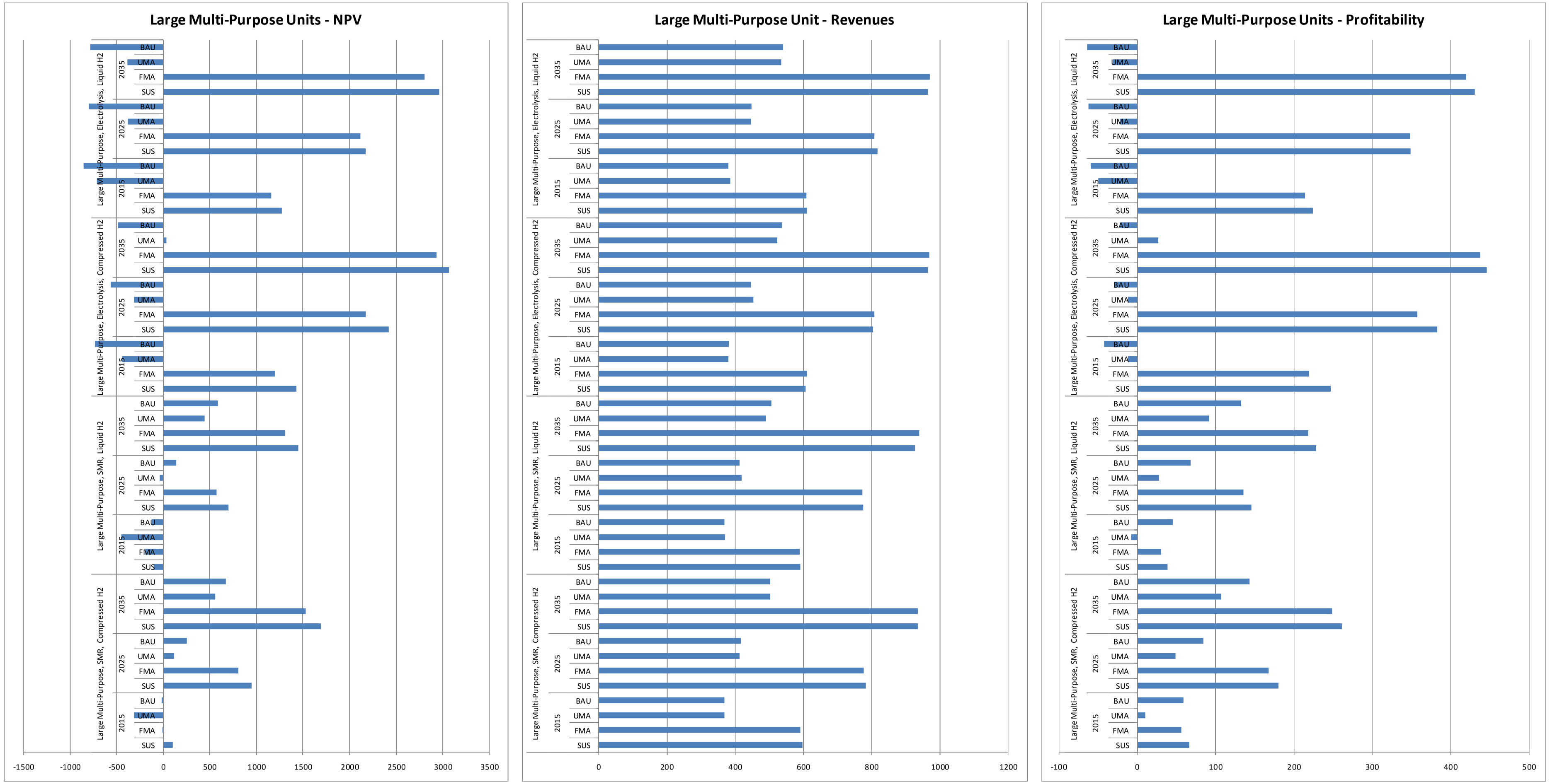



Figure 4.54 Results of Monte Carlo Scenario Simulation for Large Scale Multi-Purpose Hydrogen Production Units

## *4.3 Presentation of the electricity plant results*

### 4.3.1 General Electricity Plant / Project Economics

Identical methodologies have been employed to investigate the performance of low carbon electricity generation plant in order to make a comparison between different types of plant and with the different variants of hydrogen module from Section 4.2.

#### 4.3.1.1 Wind Plant

The different configurations of wind plant demonstrate roughly similar performance characteristics with NPVs generally increasing over time along with revenues and profits under base-case conditions as illustrated in Figures 4.55 to 4.57. The large offshore plant display declining NPV initially until the benefits of capital cost improvements start to take hold. All plant types have positive NPV and profitability from the first year of analysis.

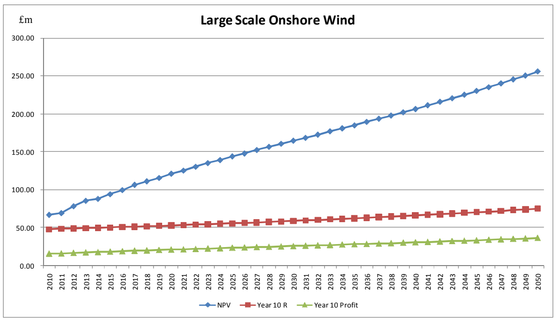



**Figure 4.55 NPV, Year 10 Profit and Year 10 Revenue for Large Scale Onshore Wind Plant**

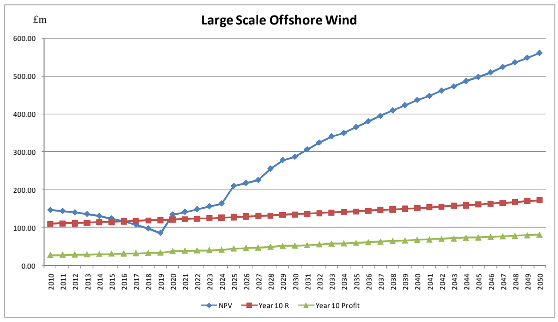



**Figure 4.56 NPV, Year 10 Profit and Year 10 Revenue for Large Scale Offshore Wind Plant**

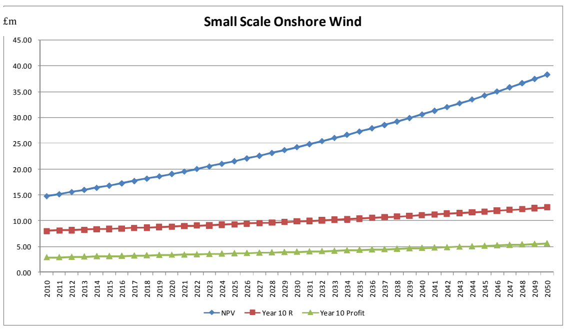



**Figure 4.57 NPV, Year 10 Profit and Year 10 Revenue for Small Scale Onshore Wind Plant**

### 4.3.1.2 Wave and Tidal Plant

The key differences observed between the wind power and wave and tidal power outputs (Figures 4.58 to 4.60) result from the decreasing levels of support forecast over time. This leads to a fall in revenues and a commensurate fall in profitability and NPV for later projects. The NPV remains positive throughout however and this suggests that either initial support levels are higher than they need to be or that the cost and revenue estimates may be optimistic. This serves to highlight the very significant impact that price support mechanisms have on the overall economics. The other observed discontinuities reflect the time at which plant starts to be introduced and therefore where learning effects start to come into play.

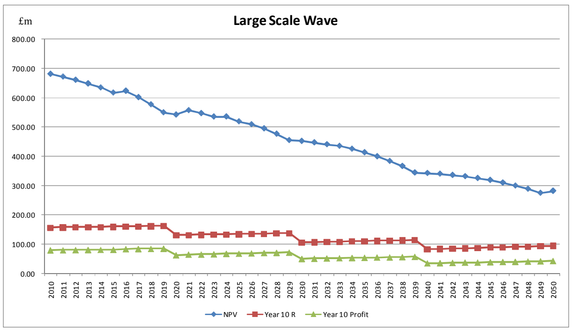



**Figure 4.58 NPV, Year 10 Profit and Year 10 Revenue for Large Scale Wave Plant**

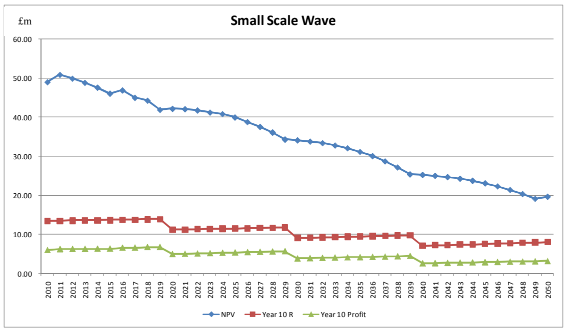



**Figure 4.59 NPV, Year 10 Profit and Year 10 Revenue for Small Scale Wave Plant**

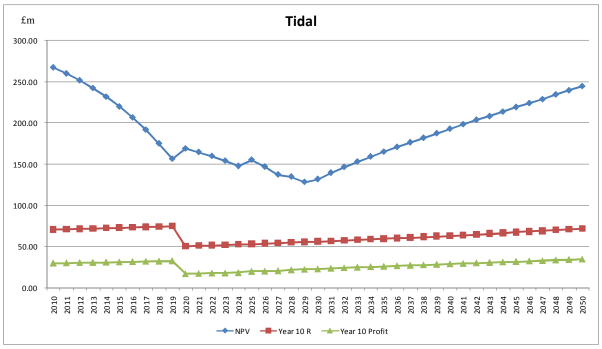



**Figure 4.60 NPV, Year 10 Profit and Year 10 Revenue for Tidal Plant**

#### 4.3.1.3 Hydro Plant

Since hydro plant is relatively mature, the economics are quite well understood and are relatively favourable despite the fact that existing hydro (represented here) does not attract the ROC payments enjoyed by newer forms of renewable generation. Revenues, profits and NPV are all monotonically increasing over time as shown in Figure 4.61 although NPVs and profits are negative reinforcing the need for price support for new hydro plant envisaged in the Renewable Obligation.

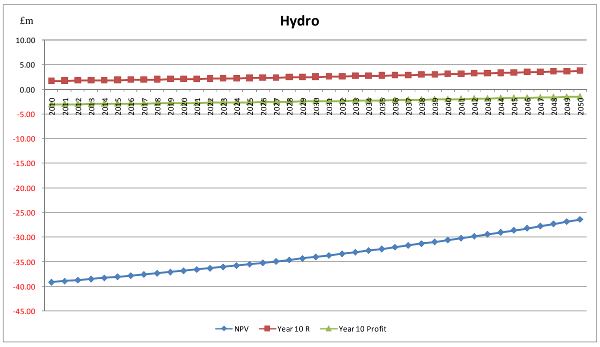



**Figure 4.61 – NPV, Year 10 Profit and Year 10 Revenue for Hydro Plant**

#### 4.3.1.4 Coal Plus CCS Plant

In terms of the Coal plus CCS plant (Figure 4.62) it should be noted that the data is highly speculative but, based on the assumed figures including, importantly, the assumption that this type of plant would attract 1.5 ROC, the analysis shows steadily increasing revenues, profits and NPV.

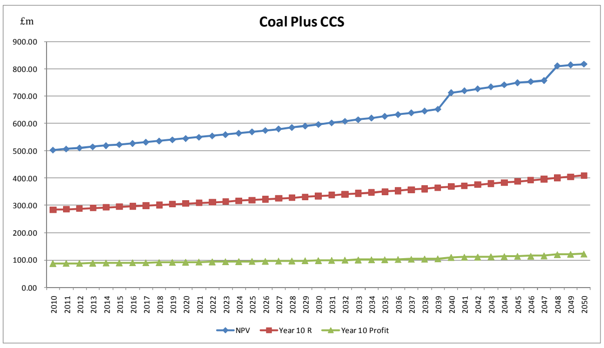



**Figure 4.62 NPV, Year 10 Profit and Year 10 Revenue for Coal Plus CCS Plant**

### 4.3.2 Sensitivity Analysis

The sensitivity indicator for low carbon electricity varies over time as shown in Figure 4.63 but not according to any obviously consistent pattern and the size of the impact varies across the different value measures. However, the results are consistent as to the input variables that are important. The economics of low carbon electricity generation plant are most affected by the electricity and ROC prices. The impact of the ROC price appears higher than the electricity price as the ROC price per MWh is higher than the wholesale electricity price (see base case costs in Table 4.3). The outputs are positively correlated with both ROC and electricity prices. Both NPV and, to a lesser extent, profits are also impacted by the investment cost and NPV is impacted by the cost of equity. As expected, a negative correlation exists between these latter input and output parameters.

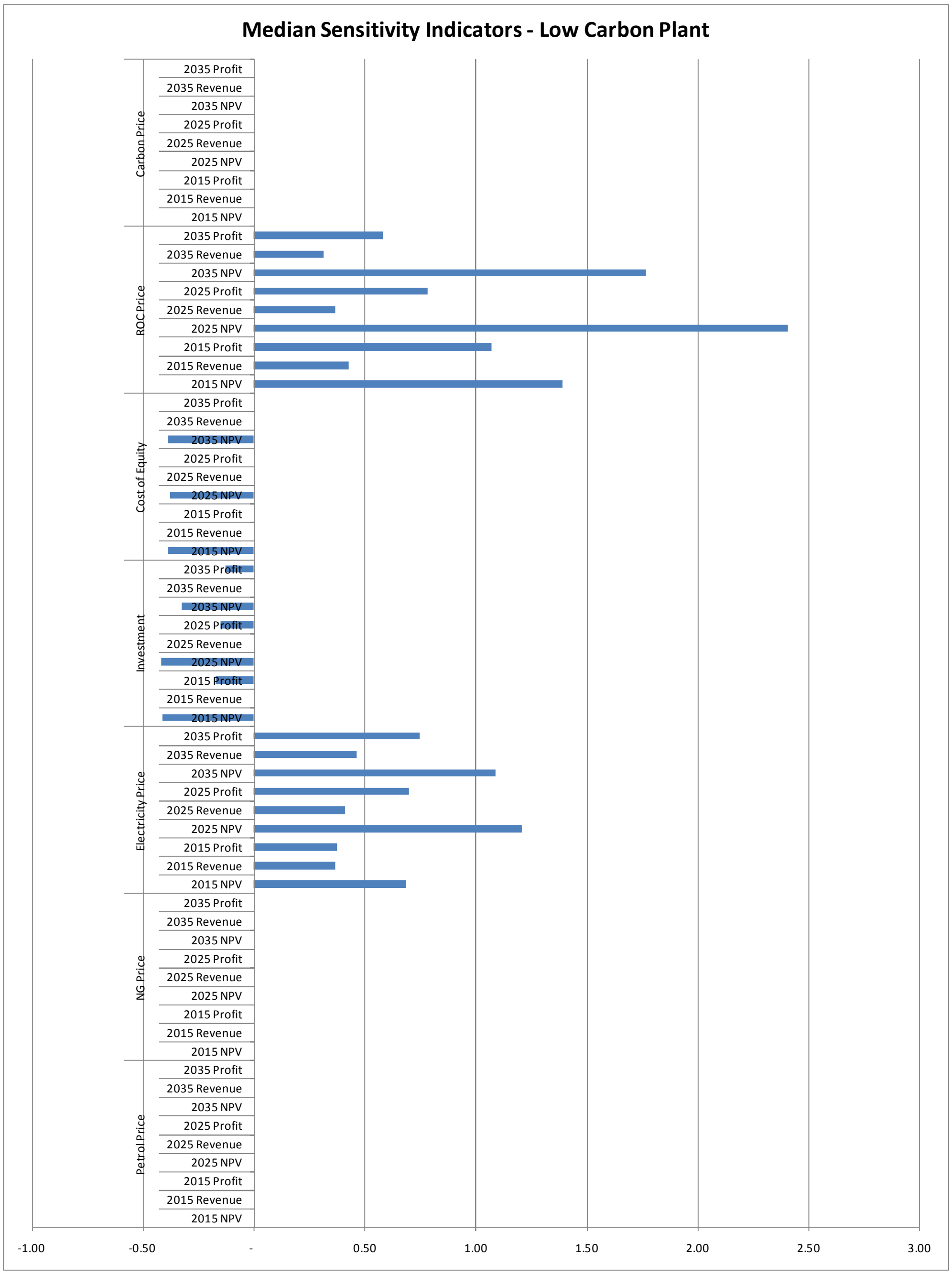



**Figure 4.63 Relative Sensitivity of Low Carbon Electricity Generating Plant to Input Variables**

The picture for coal plus CCS (Figure 4.64) is similar except that now the price of coal is an additional input variable having some impact on the results.  At the same time the investment costs demonstrate a lower impact underlining the lower relative contribution of the investment costs to the overall lifetime costs of the plant.

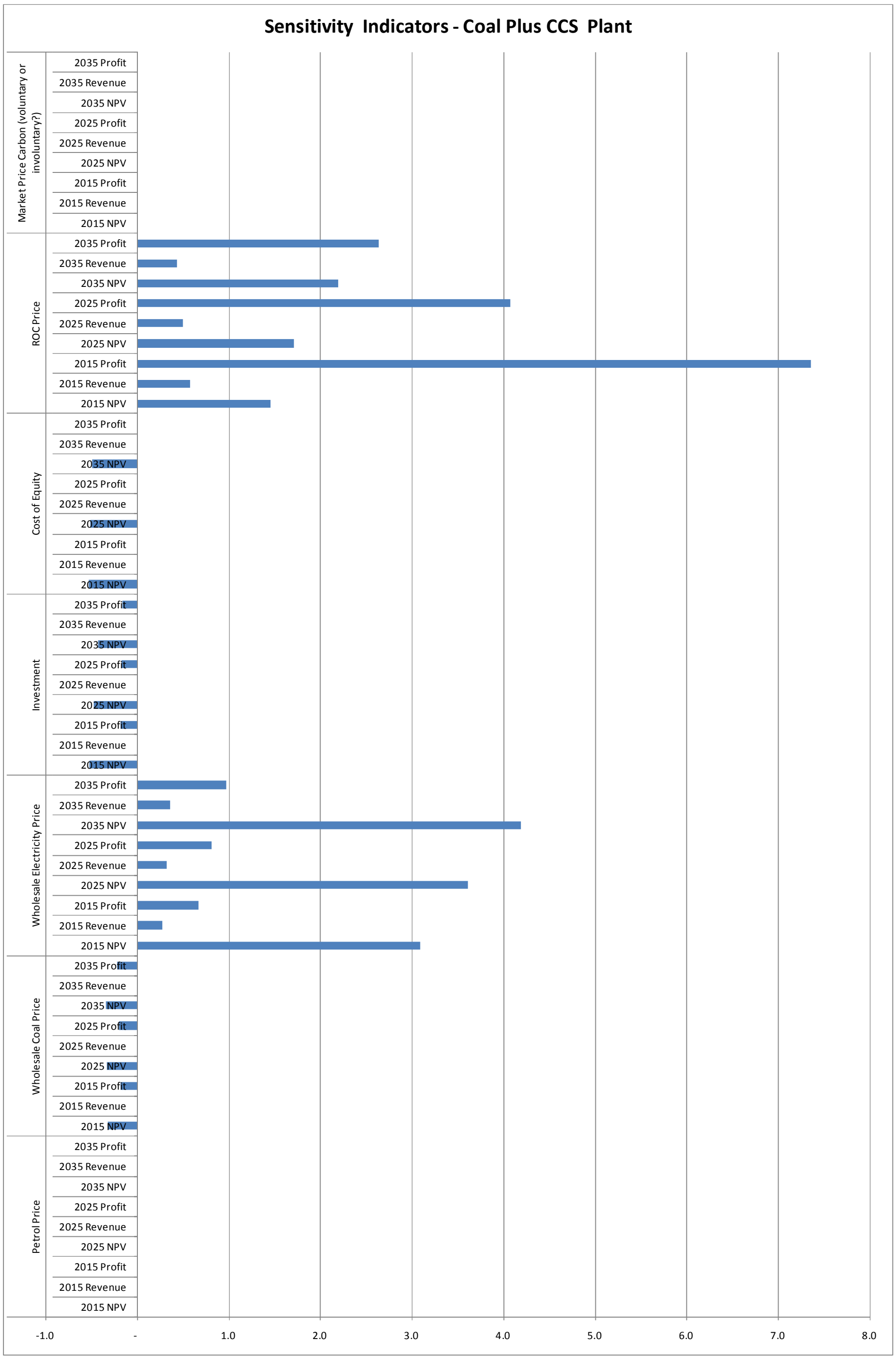



**Figure 4.64 Relative Sensitivity of Coal Plus CCS Plant to Input Variables**

### 4.3.3 Probability Weighted Analysis

When the probability weighted analysis is considered, all types of wind plant show increasing revenues, profits and NPV over time, as shown in Figures 4.65 to 4.67, with large offshore wind ultimately delivering higher NPV. Given the greater scale of the Large Offshore wind plant, the revenues and profits of these plant are consistently higher than the Large and Small Onshore wind plant. However, the NPV is initially lower before finishing higher in later years as learning takes effect.

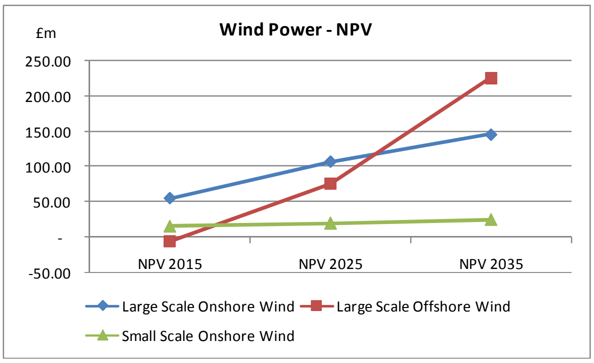



**Figure 4.65 NPV Probability Weighted Sensitivity Analysis Wind Plant**

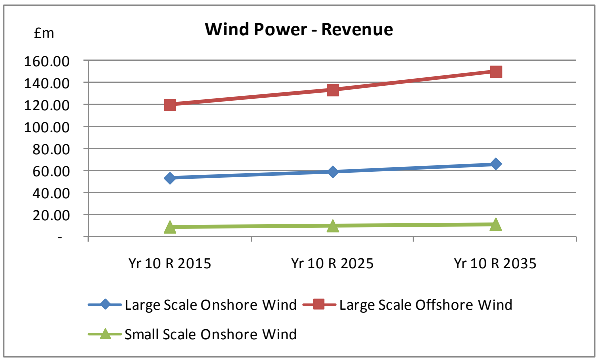



**Figure 4.66 Year 10 Revenues Probability Weighted Sensitivity Analysis Wind Plant**

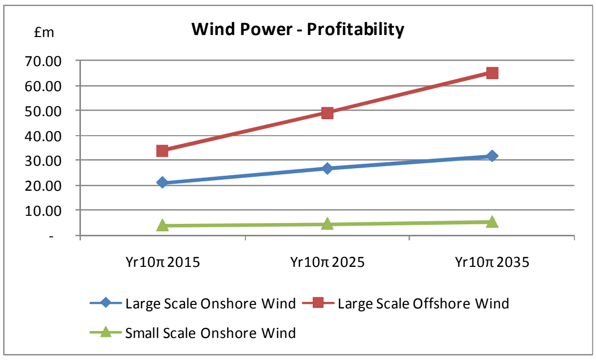



**Figure 4.67 Year 10 Profits Probability Weighted Sensitivity Analysis Wind Plant**

Consistent with the effects observed in Section 4.3.1.2, marine and tidal plant demonstrate declining revenue, profits and NPV for the reasons already explained. The NPVs for both small scale wave and hydro plant are negative in both instances driven by poor profitability performance (see Figures 4.68 to 4.70).

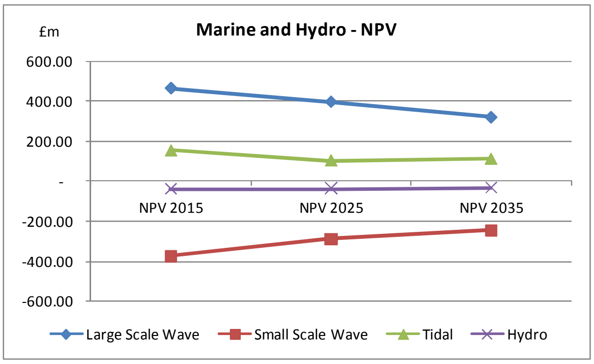



Figure 4.68 NPV Probability Weighted Sensitivity Analysis Marine and Hydro Plant

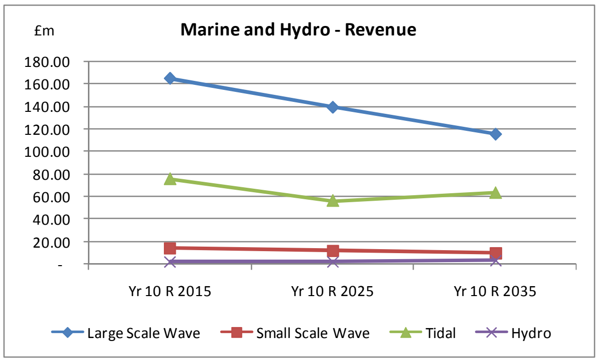



Figure 4.69 Year 10 Revenues Probability Weighted Sensitivity Analysis Marine and Hydro Plant

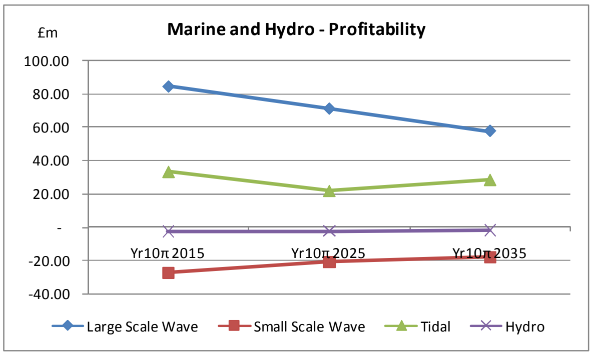



Figure 4.70 Year 10 Profits Probability Weighted Sensitivity Analysis Marine and Hydro Plant

The coal plus CCS plant demonstrates economics which are potentially significantly positive on all fronts as illustrated in Figure 4.71.

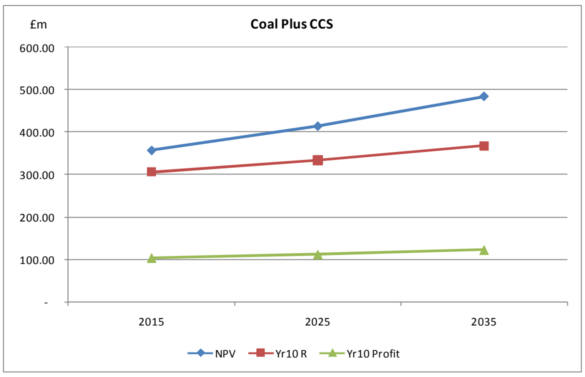



Figure 4.71 NPV, Revenue and Profit Based Probability Weighted Sensitivity Analysis Coal Plus CCS Plant

### 4.3.4 Scenario Analysis

The first thing to note when looking at the results from the scenario analysis provided in Figures 4.72 to 4.74, from the scenario analysis for the electricity plant is that there is relatively less variability between the different scenarios than is observed for the hydrogen plant. The likely explanation for this is that amongst the variables considered in the analysis, a greater number have a direct effect on hydrogen plant as compared with electricity plant. It is also the case that the sensitivity of electricity plant to the input variables is relatively lower than for the hydrogen plant.

The picture is quite consistent across the broad range of plant considered which again is in contrast with the hydrogen plant. This results from the fact that in reality there is a greater degree of homogeneity displayed by the electricity plant as compared with the hydrogen plant since, with the exception of the Coal plus CCS plant, all plant types have quite similar economic characteristics. Fuel costs are zero and the vast majority of the lifetime costs result from the capital costs. The hydrogen plant meanwhile has a significant element of fuel costs, being supplied either by electricity or natural gas, which adds a degree of complexity. Confirming these points, the Coal plus CCS plant shows a set of characteristics more in line with the larger hydrogen plant than with the renewable generation plant. Overall, the majority of the electricity generation plant types demonstrate positive economic performance across the range of scenarios; this is again in contrast with the hydrogen plant.

Probably the most surprising result is the fact that in the case of the wind plant the apparently less favourable scenarios yield higher results. The explanation for this is the relative state of maturity of wind compared with other renewable plant since when the marine and hydro plant is considered it can be noted that the reverse is generally true. The ROC price affects all renewable generation plant but it affects the wind plant less since it attracts fewer ROCs than other plant under the multiple ROC regime. It is interesting that the differences observed diminish over time as the marine plant start to attract fewer ROCs reflecting decreasing need for support. The other thing to note is that the other axis in the scenario analysis is the price of fossil fuels which in reality do not impinge at all on the absolute economics of the renewable generation plant. However, it is worth pointing out that there is a second order effect linking the price of electricity and oil which could be explored in a later iteration of the model. Coupled with this is the price of carbon which is higher in the "favourable" scenarios and lower in the "unfavourable" ones. Fossil fuel and carbon prices only become relevant when considering the *relative* economics of renewable plant versus fossil fuel plant so while they are important and relevant factors for the overall analysis as will be discussed in Chapter 5, the importance in terms of the absolute analysis is negligible.

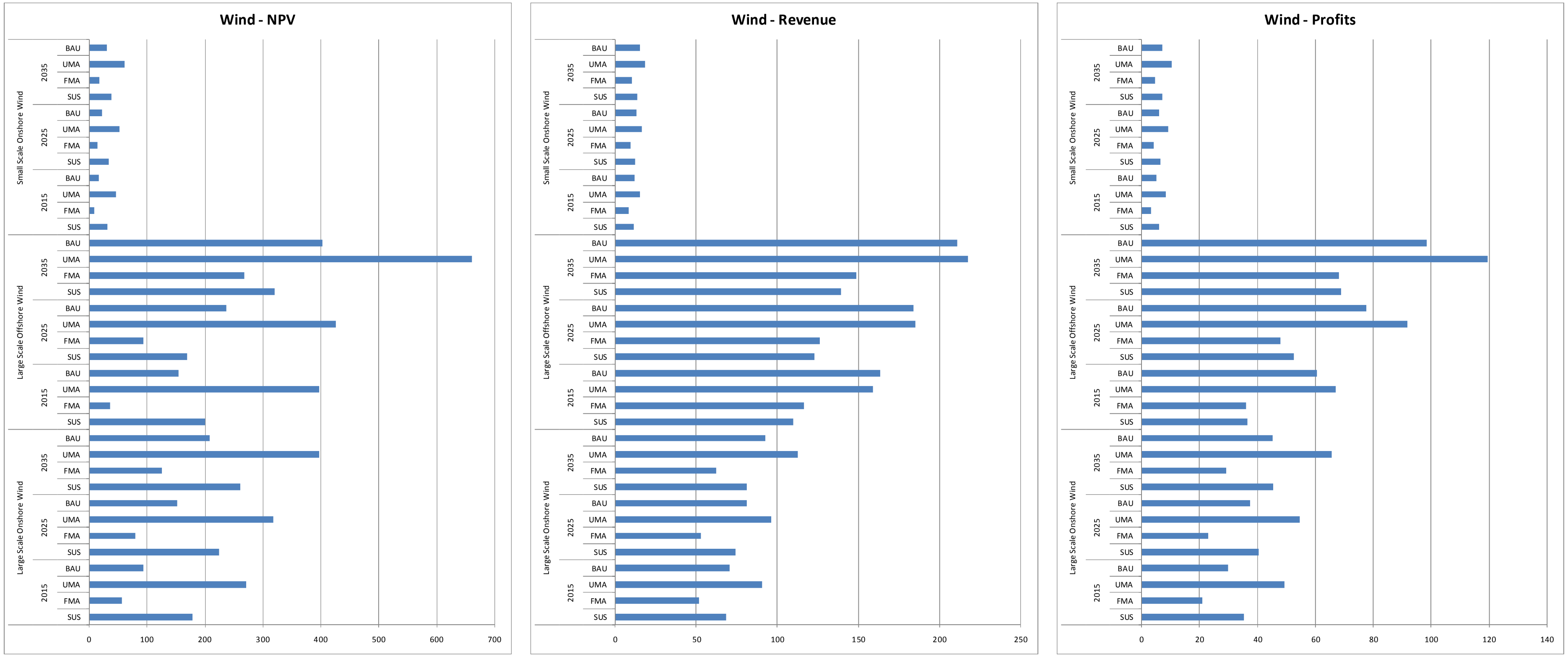



**Figure 4.72 Results of Monte Carlo Scenario Simulation for Wind Power Plant**

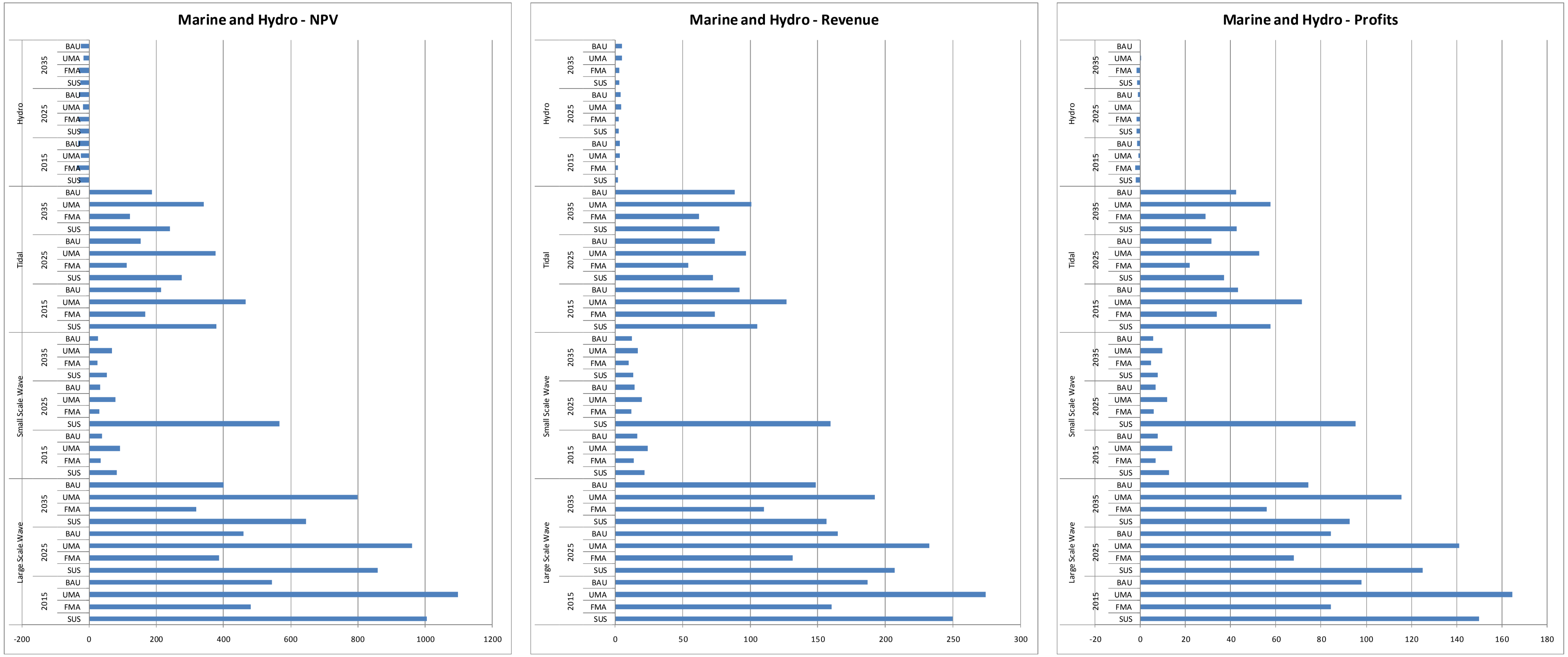
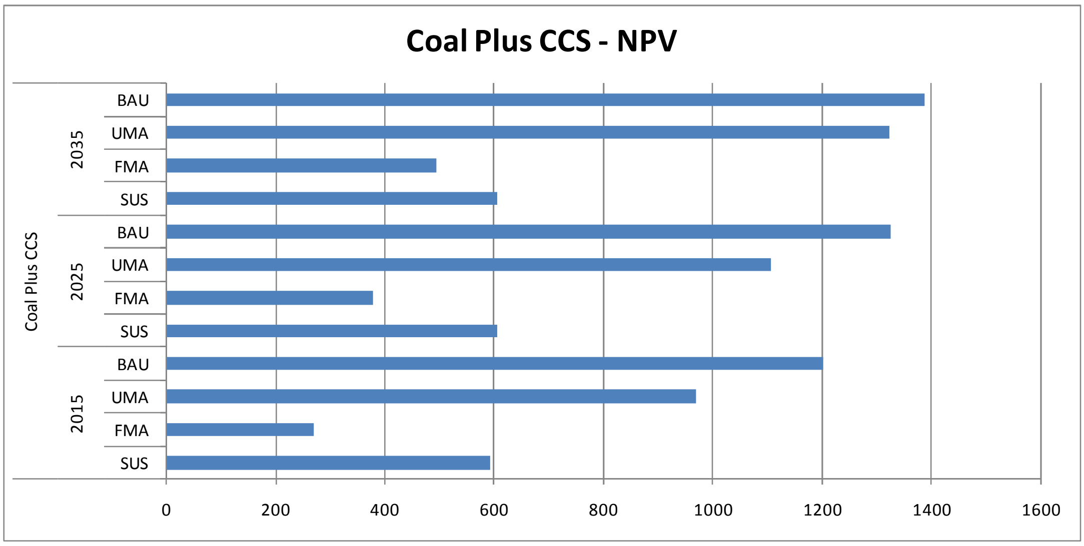
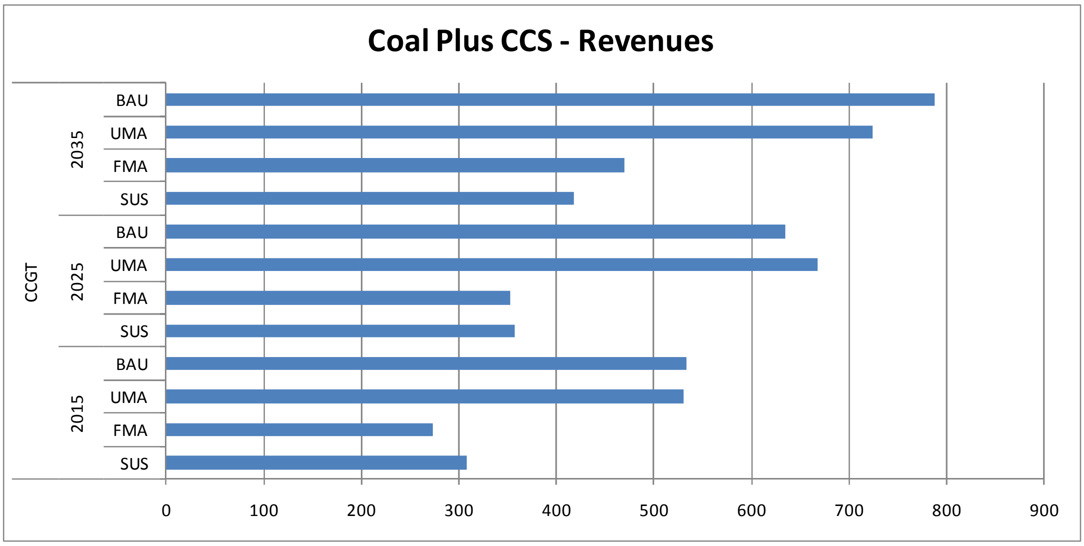



Figure 4.73 Results of Monte Carlo Scenario Simulation for Marine and Hydro Power Plant



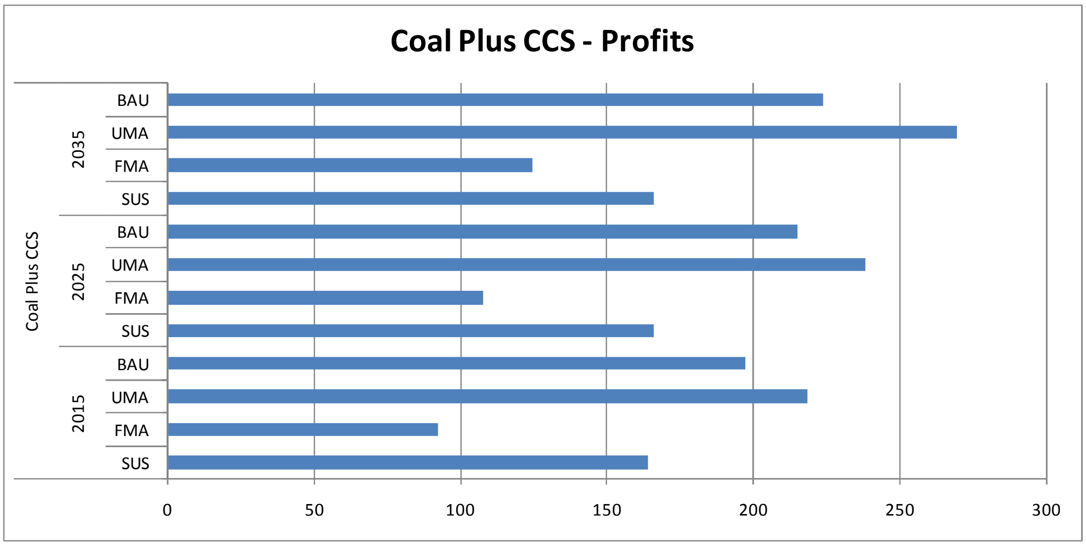




**Figure 4.74 Results of Monte Carlo Scenario Simulation for Coal Plus CCS Power Plan**

## 4.4 Relative Economics Across Energy Types

In this section the author provides an absolute comparison of hydrogen and electricity projects offering insights into the decisions companies might take when faced with the option of investing in either renewable generation or hydrogen infrastructure. It is unlikely that any investment decision will be made in isolation and companies will typically be subject to capital constraints to a lesser or greater degree and must therefore choose between the investment opportunities open to them at any given time. The model developed here assumes that all things being equal companies will allocate capital according to where returns are highest and in such a way as to maintain risk at an "acceptable" level. As has been discussed previously, the capital available might consist of internal funds, that is to say cash reserves or retained profits, as well as external funds in the form of loans or capital raised through the issuance of new equity or quasi equity (convertible bonds, for example). Such external fund-raising may be directly linked to the investment being made, which is the typical structure for so called project financed transactions, or may be simply earmarked for general growth. Most large infrastructure projects, at least where the technology is well established, are financed through project financing with the capital structure being directly linked to the specific investment being made.

Consequently, when building up the forecast model it is worthwhile examining the relative economics of different types of project since this will affect the investment decisions made by companies looking to enter and develop the hydrogen energy sector. One way of examining this is to consider the way in which the relative economics of different "competing" projects change as key input parameters are varied. For example, it is easy to imagine that if the price of transport fuel were to increase in absolute terms and relative to the price of electricity this would tend to increase the likelihood that a utility would invest in hydrogen energy infrastructure directed towards transport fuel. Not only would the absolute price level achievable for each unit of hydrogen increase but in addition the differential between the input energy costs and the output price would also increase.

Two specific paired variables have been analysed, namely the electricity and petrol prices and the cost of capital and policy measures. The findings of these analyses are presented in the following sections.

### 4.4.1 Electricity / Petrol Fuel Price Differential

Figure 4.75 presents the NPV of the electrolysis compression refuelling station modules as petrol price and electricity price are varied. Each line represents an iso-electricity-price curve while project NPV in 2015 is plotted along the y-axis and petrol price along the x-axis. Figure 4.76 presents the same data for the 2035 reference year.

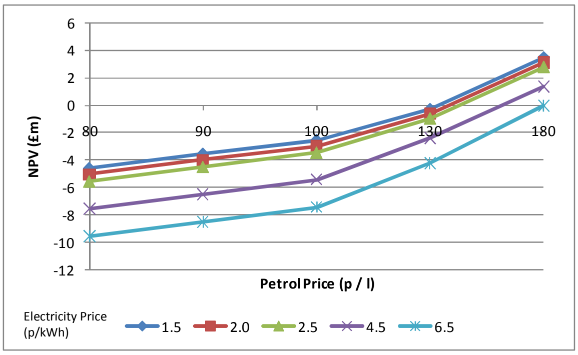



**Figure 4.75 Variation of NPV with Electricity and Petrol Price 2015 (REC)**

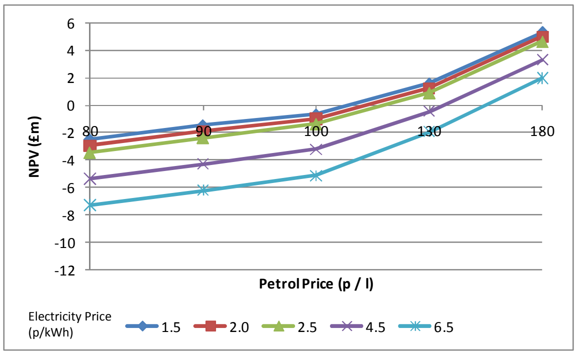



**Figure 4.76 Variation of NPV with Electricity and Petrol Price 2035 (REC)**

As would be expected, the NPV increases with increasing transport fuel price while NPV worsens as the electricity price increases reflecting the increased input costs. The NPV is generally higher in 2035 reflecting the improving economics of the plant as discussed in Section 4.2.1. Figures 4.77 to 4.80 present the same data for micro and mid size multi-purpose units.

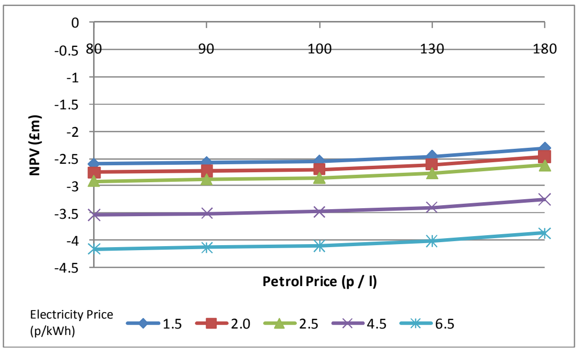



**Figure 4.77 Variation of NPV with Electricity and Petrol Price 2015 (SMEC)**

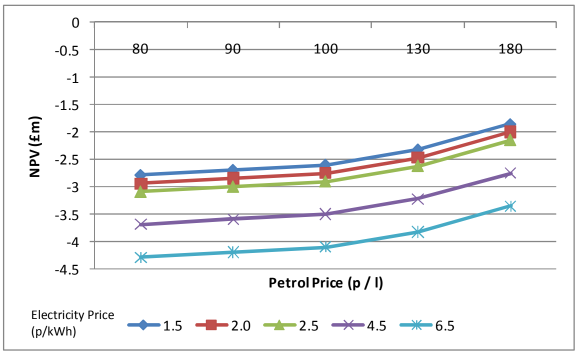



**Figure 4.78 Variation of NPV with Electricity and Petrol Price 2035 (SMEC)**

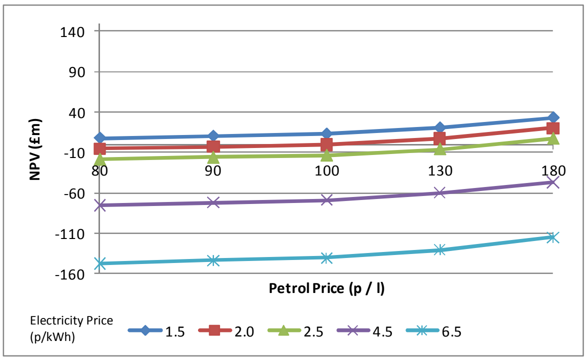



**Figure 4.79 Variation of NPV with Electricity and Petrol Price 2015 (LMEC)**

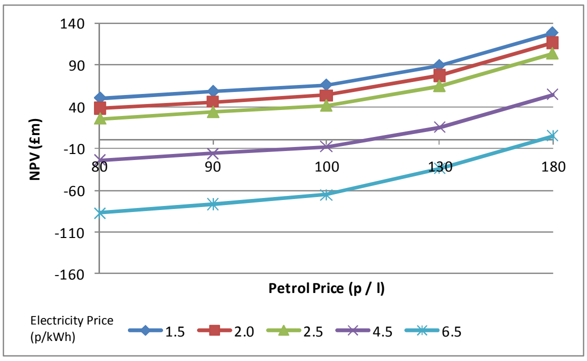
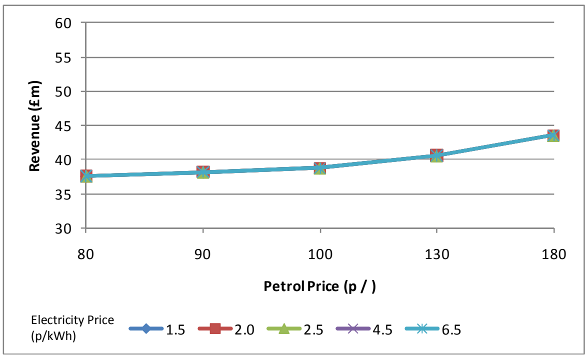



**Figure 4.80 Variation of NPV with Electricity and Petrol Price 2035 (LMEC)**

By way of comparison, Figures 4.81 and 4.82 present revenue data for the mid-size plant. As can be seen, the revenue increases with petrol price but is unaffected by the electricity price since this only affects the plant costs not the revenues.



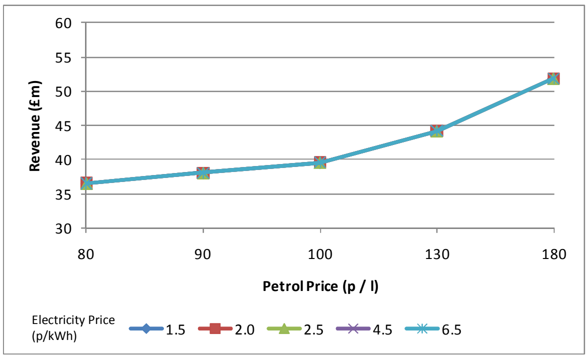
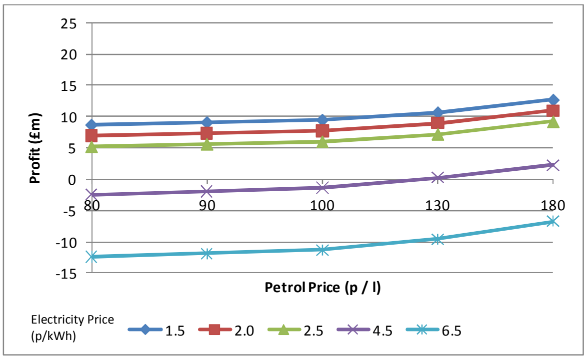




**Figure 4.81 Variation of revenue with Electricity and Petrol Price 2015 (LMEC)**

**Figure 4.82 Variation of revenue with Electricity and Petrol Price 2035 (LMEC)**

Finally in Figures 4.83 and 4.84 the profitability data for the mid-size plant is presented which follows a similar pattern to the NPV data.



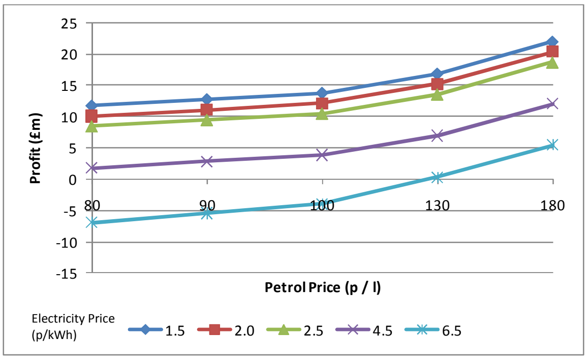




**Figure 4.83 Variation of profit with Electricity and Petrol Price 2015 (LMEC)**

**Figure 4.84 Variation of profit with Electricity and Petrol Price 2035 (LMEC)**

Having briefly examined the variation of the performance of the hydrogen plant with variations in the electricity price and the petrol price, the same analysis is made with respect to renewable plant. The picture looks very similar across all types of renewable generation and so only a single example is presented here, namely the large onshore wind plant in 2015 and 2035. Once again iso-electricity-price curves are plotted and the NPV is tracked according to a range of petrol prices. In contrast to the hydrogen plant, the wind generation plant NPV is unaffected by variations in the petrol price but increases in relation to the electricity price as shown in Figures 4.85 and 4.86.

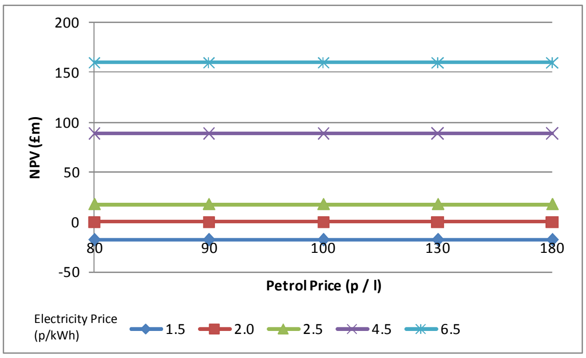



**Figure 4.85 Variation of NPV with Electricity and Petrol Price 2015 (Large Onshore Wind)**

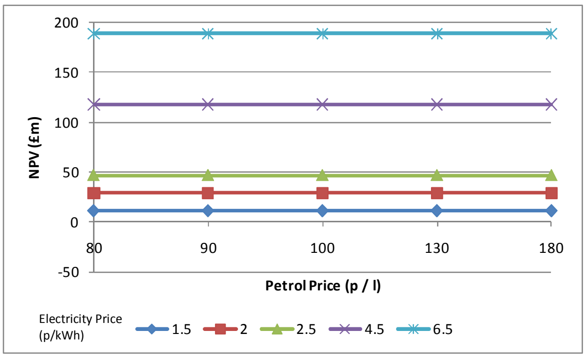



**Figure 4.86 Variation of NPV with Electricity and Petrol Price 2035 (Large Onshore Wind)**

Figure 4.87 presents the combined results for a single example, a small onshore wind plant and a mid size electrolysis compression multi-purpose unit. These have been chosen since the size of the two plants is of the same order of magnitude and hence provide a reasonable like-for-like comparison. As seen in Figures 4.85 and 4.86, the electricity plant iso-price NPV curves are flat whereas the hydrogen plant (see Figures 4.75 to 4.80) iso-price NPV curves increase at an increasing rate with petrol price. For an electricity price of 1.5 pence / kWh the hydrogen plant NPV is always higher than the generation plant NPV. However, as the electricity price increases the combined effect of reducing NPV for the hydrogen plant and increasing NPV for the generation plant means that the relative economics of the electricity plant gradually outstrips the hydrogen plant. For an electricity price of 2.0 pence / kWh, the hydrogen plant has better economics for petrol prices in excess of approximately 130 pence / litre (slightly higher than the current price) while for electricity prices of 2.5 pence / kWh (the base case scenario) and above, the NPV of the generation unit is always higher than for the hydrogen unit. What the preceding analysis serves to confirm is that there are conditions under which hydrogen projects might find investment ahead of renewable generation projects and vice versa depending on the prevailing conditions.

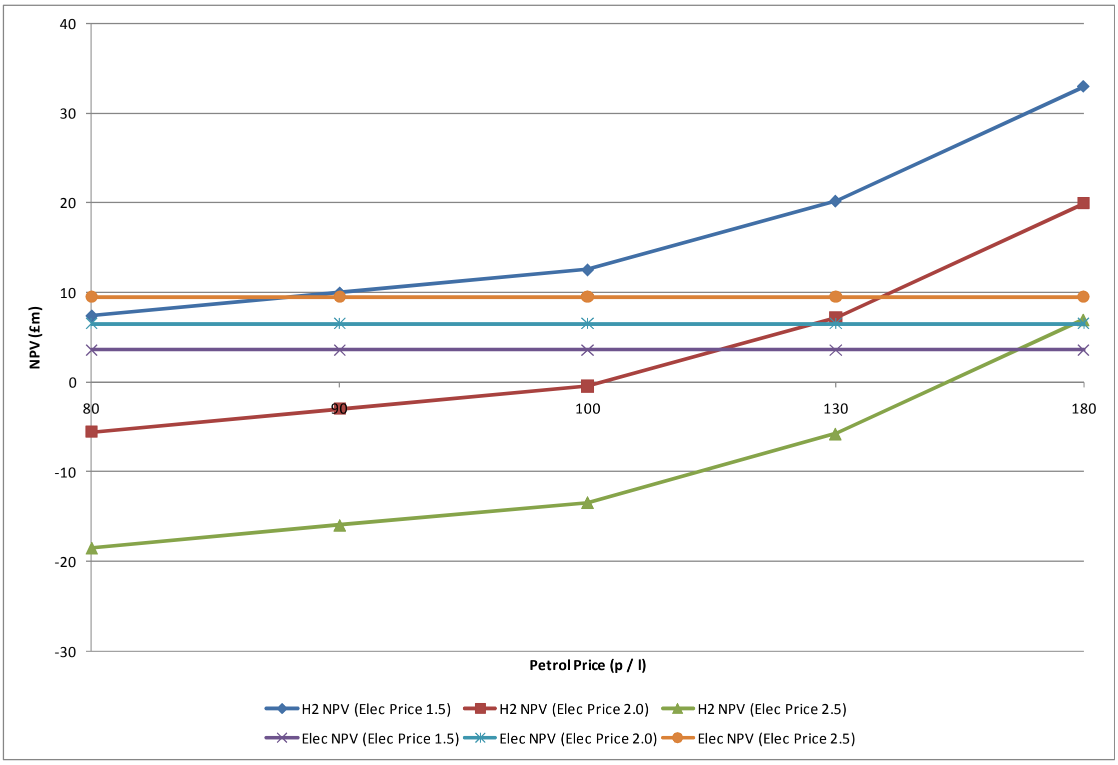



**Figure 4.87 Comparison of Hydrogen and Electricity Plant NPV as Petrol and Electricity Prices are varied**

This has important implications for policy makers since support for one low carbon activity might be at the expense of another. Indeed what the analysis presented in Figure 4.87 seems to suggest is that commensurate levels of support (price support or other) would be required in order for investments in hydrogen to appear as attractive as renewables investments. This is discussed further in Section 4.4.2.

### 4.4.2 Cost of Capital / Policy Measures

As was discussed in Section 2.4 the government has put in place a number of measures to either stimulate the development of low carbon technologies or to penalise the use of fossil fuels. These include the Renewable Obligation [45] and the Renewable Transport Fuel Obligation [48] the effect of which can be considered in isolation as was demonstrated in the sensitivity analysis (see Sections 4.2.1 and 4.3.2). However, when considering the investment opportunities open to companies it might be necessary to compare the effect of the two sets of policy measures across projects. If a given company or group of companies is expected to be comparing investment in hydrogen infrastructure or electricity generation, for instance, it is essential to compare the impact of both policy measures across the two technologies and across the different types of investing companies. Given that another significant input to the NPV calculation would be the cost of capital, the output of the model is recorded as both the level of policy support, and the cost of capital, are varied.

Figures 4.88 and 4.89 present the NPV of the small electrolysis compression refuelling units as the cost of capital and RTFO (TOC Plus Duty Benefit) support level are varied in the reference years 2015 and 2035. Iso-RTFO lines are plotted to show the variation in NPV with discount rate. The results for the higher support levels follow the expected pattern, with the NPV levels reducing as the cost of capital increases. By contrast, at lower levels of support the NPV increases with increasing cost of capital which is counter-intuitive. The reason for this is that for lower levels of support cash flows are negative throughout the lifetime of the project and hence a higher cost of capital actually serves to increase the NPV. What these charts suggest is that the levels of support through the RTFO are currently below where they would need to be in order to encourage investment in hydrogen plant in 2015 but, in absolute terms, at a satisfactory level for 2035 (i.e. providing positive NPV).

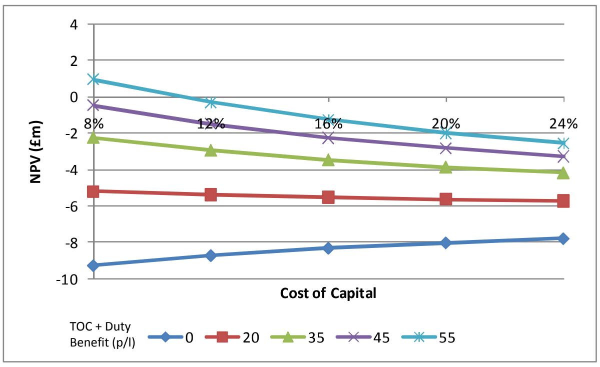



**Figure 4.88 Variation of NPV with TOC Price and Cost of Capital, Small REC 2015 Plant**

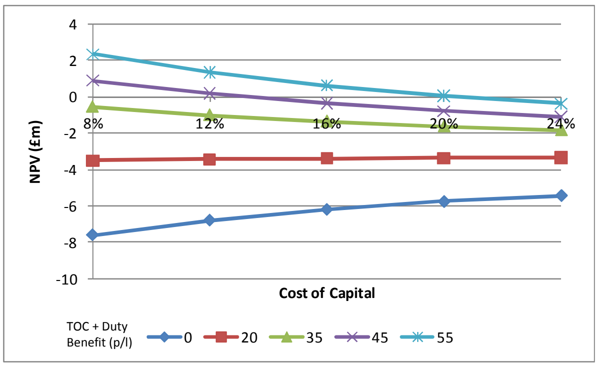



**Figure 4.89 Variation of NPV with TOC Price and Cost of Capital, Small REC 2035 Plant**

Figures 4.90 to 4.93 present the same data for the micro and mid-size multi-purpose units. The micro units display the increasing curves across the range of policy support levels given the negative cashflows throughout the range. The mid-size units on the other hand display a more "traditional" pattern.

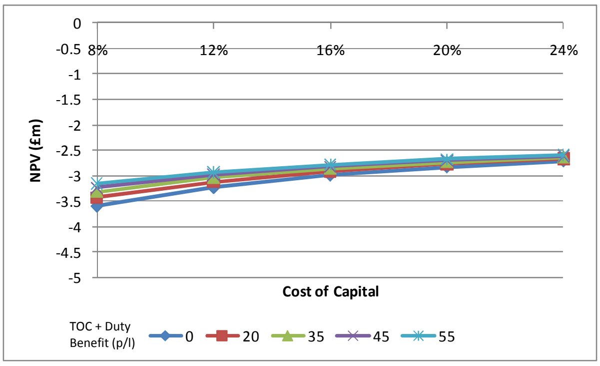



**Figure 4.90 Variation of NPV with TOC Price and Cost of Capital, Micro Scale MEC 2015 Plant**

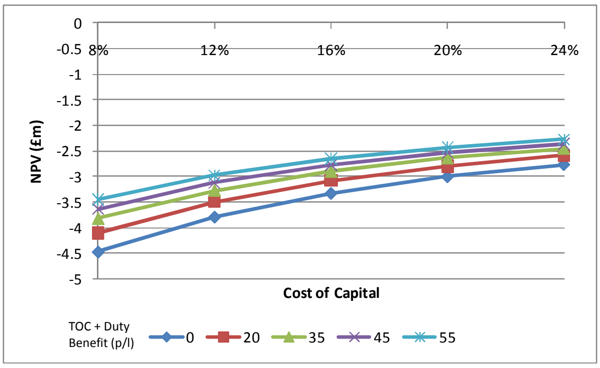



**Figure 4.91 Variation of NPV with TOC Price and Cost of Capital, Micro Scale MEC 2035 Plant**

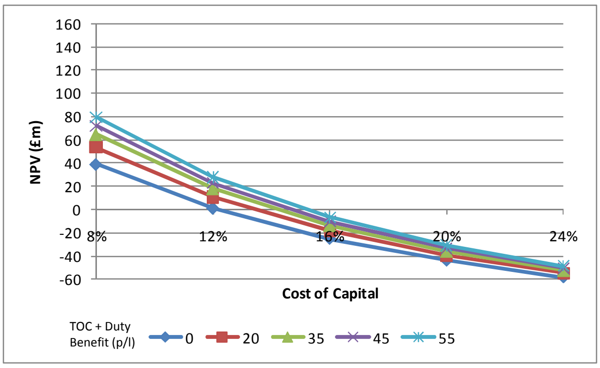



**Figure 4.92 Variation of NPV with TOC Price and Cost of Capital, Mid Scale MEC 2015 Plant**

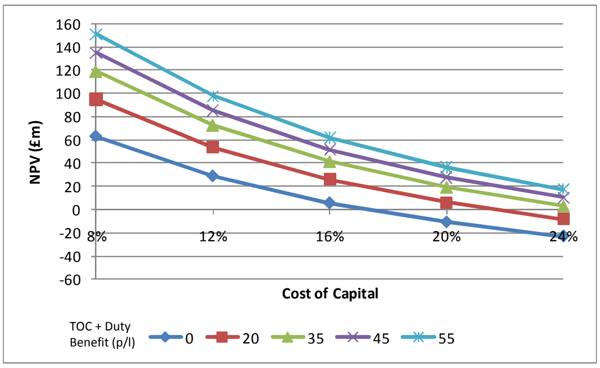



**Figure 4.93 Variation of NPV with TOC Price and Cost of Capital, Mid Scale MEC 2035 Plant**

Figures 4.94 and 4.95 present the iso-RTFO profitability curves for the mid size units which do not vary according to the cost of capital. This results from the fact that it is the cost of equity that is varied, while the cost of debt is held constant, which means that the profitability is unaffected. It should be noted that, changes to the cost of debt would feed through to the profit since this would affect the level of interest paid.

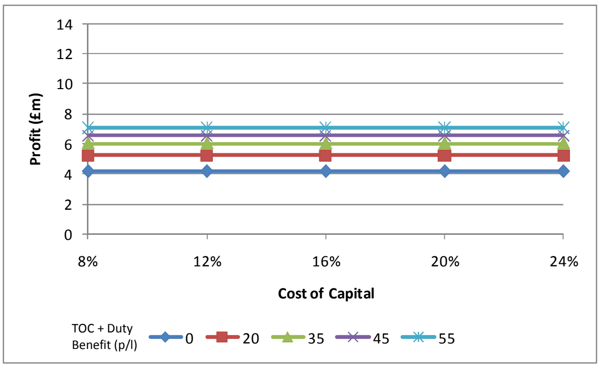



**Figure 4.94 Variation of Year 10 Profit with TOC Price and Cost of Capital, Mid Scale MEC 2015 Plant**

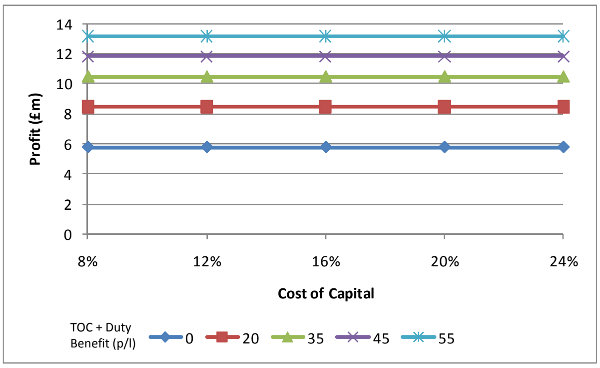



**Figure 4.95 Variation of Year 10 Profit with TOC Price and Cost of Capital, Mid Scale MEC 2035 Plant**

Figure 4.96 and Figure 4.97 presents the data for the small scale onshore wind generation plant. In this instance it is the iso-RO price NPV curves that are plotted across the range of discount rates. The curves follow the more recognisable pattern displayed by the mid size multi-purpose hydrogen units.

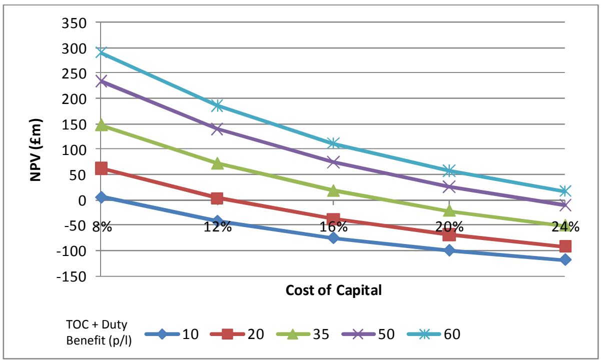



**Figure 4.96 Variation of NPV with ROC Price and Cost of Capital, Onshore Wind 2015 Plant**

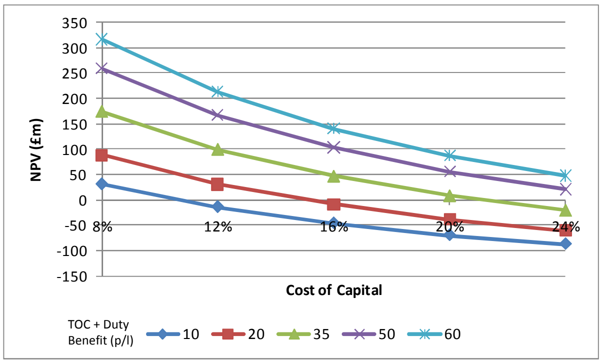
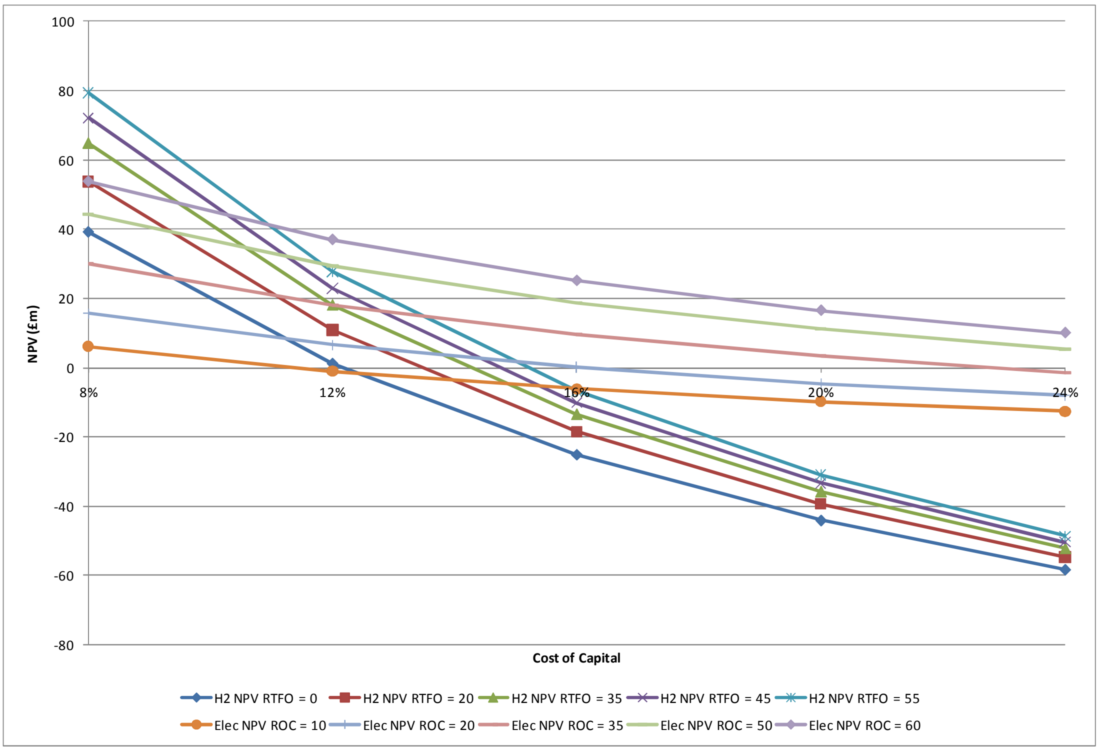



**Figure 4.97 Variation of NPV with ROC Price and Cost of Capital, Onshore Wind 2035 Plant**

The relative effects on the NPV of changes to the policy measures and discount rate are now explored with reference to a mid-size electrolysis compression hydrogen plant and a small scale onshore wind generation plant as in the previous section. Figure 4.98 presents the results as the ROC and RTFO levels are varied.




*Note: RTFO refers here to the total TOC + fuel duty benefit*

**Figure 4.98 Comparison of Hydrogen and Electricity Plant NPV as Cost of Capital and RTFO + Fuel Duty Benefit are Varied**

It can be observed that at lower levels of cost of capital the hydrogen projects appear to show better NPVs whatever the levels of policy support. However, at higher levels of capital cost the reverse is true. If the level of support for hydrogen infrastructure is at its highest level and for renewable electricity at its lowest level then the hydrogen project would find favour at all levels of cost of capital up to 16%. If support for the renewable generation sector is at its highest level however, this figure falls to 11%. Where support is at its lowest level for both types of project the NPV equality cost of capital is 12%.

Once again, this analysis highlights the fact that different conclusions may be drawn when markets are considered in tandem rather than in isolation. If the support levels to be applied to a particular market are set so as to enable companies to achieve a certain level of return on investment this may be considered to represent an adequate incentive. However, such incentives may still fail to encourage investment in that sector if support levels elsewhere allow companies to achieve better returns in other industries. It is therefore of critical importance to ensure that in situations where companies may be able to freely cross between different sectors that the relative as well as the absolute levels of support are considered.

## *4.5 Chapter Summary*

In general, the model indicates that hydrogen plant can deliver positive NPVs and profitability from a relatively early stage in the period modelled (see Figures 4.3 to 4.28). The initial evidence, therefore, hints at the possibility that the results from cost optimisation models, which see hydrogen being introduced much later (see, for example, the UK Strategic Framework [12]), might be overly pessimistic. There is an argument to say that if scope exists for organisations to make sufficient returns, indicated by a positive NPV, there will be entrepreneurs willing to exploit the opportunity even if the returns may be lower than can be obtained elsewhere. However, while at first glance the analysis suggests that hydrogen projects could be developed in an early timeframe, needless to say, this *will* be in part dependent on whether these projects are relatively more attractive than other projects that exist.

Leaving aside the financial implications, it is worth considering the strategic aspects of such investment decisions. A company looking to develop a particular market is likely to favour projects within its current horizon of expertise which, if NPV positive, it will be keen to exploit. For example, an electricity utility might find the development of a large wind farm and an associated hydrogen production plant to be well within its horizon. By contrast, it might consider that building a biofuel refinery is not, even if NPV positive. Thus, while a biofuel plant might, in theory, be able to offer better returns than a renewables plus hydrogen plant, it does not automatically follow that the company will favour the biofuels investment option. Thus, as long as the wind plus hydrogen option can maximise returns to the company among those projects available (i.e. within its horizon) then there is a reasonable chance that it will be developed. The cost-optimisation approach meanwhile, takes a systems based view and may overlook the differences that exist between companies in a privatised market where decisions are made on the value enhancement that investment projects can offer for a given level of risk. While these strategic aspects do not fundamentally change the view that company investment decisions will be driven by the desire to maximise value, it helps to inform the choice of discount rate, or the choice of parameters for the sensitivity and stochastic analysis, or both.

It is no surprise, but worth reiterating, that the hydrogen plant value measures are highly sensitivity to the price of petrol and, by implication, the price of hydrogen. By contrast the TOC price seems to have relatively little effect suggesting that the level might be too low to provide any meaningful support to hydrogen energy infrastructure investment (see Figures 4.29 and 4.30). What this serves to highlight is that it is highly possible, given the high volatility of the oil price, that changes to the underlying price dwarf the effect of any measures to stimulate uptake of alternatives. What is more, energy policy makers face a dilemma in that while high fossil fuel prices undoubtedly have a positive effect on the *relative* viability of alternative low carbon technologies they also serve to entrench the position of fossil fuel producers. To put it another way, it might be optimistic to think that an oil company will be encouraged to invest in alternative energy while the oil price is high since, by implication, returns to oil investments are also high. This is reinforced by the fact that, as was shown in Table 2.12, the price elasticity of demand is very low in the short term and only a sustained and significant change in fossil fuel prices is likely to invoke the kind of behavioural change required for the very long term investments required to shift wholesale to alternatives. In contrast, companies involved in activities other than oil and gas, such as electricity utilities, which do not benefit directly from higher oil prices, may indeed find the attractiveness of hydrogen projects to increase as the oil price increases.

The probability-weighted sensitivity analysis (see Figures 4.31 to 4.48) provides a useful distillation of the results from the base case and sensitivity analyses and confirms the general picture as to the patterns of NPV, revenues and profits over time. It is worth mentioning two aspects to this analysis which could be further explored in a future iteration of the model. The first would be to widen the sensitivity range and / or change the probability weightings for the later analysis years to reflect the greater uncertainty that might be expected to exist with respect to projections further into the future. The other would be to consider the analysis as a decision tree with the outcomes in future years being, in part, dependent on decisions taken in earlier years of the analysis. These approaches were not applied to the current research since the purpose was primarily to test the underlying premise of the model but they may be useful embellishments for the future.

In terms of the scenario analysis, it is interesting to note that the bifurcation between the “positive” and “negative” scenarios is much less marked for the larger series of plant than for the smaller plant (see Figures 4.49 to 4.54). The implication is that the relative impact of changes to policy and fuel price may differ significantly even within one technology. As will be seen in Chapter 5, the introduction of the companies into the equation creates an even greater degree of complexity and highlights the benefits of examining the problem from more than one perspective.

Looking at the renewable electricity sector, perhaps the most important high level result is that all renewable electricity technologies show positive NPVs and profitability more or less across the whole period of analysis suggesting the current levels of support are at least adequate (see Figures 4.55 to 4.62). What is particularly interesting is that the results for marine technologies (wave and tidal, see Figures 4.58 to 4.60) show a diminution in NPV and profitability over the period as the support levels in the model are decreased over time. This might suggest that the current levels are higher than they need to be since while NPV levels are lower than for other more established technologies they are still positive. Nevertheless, it is true to say that in the current scenario, a company intent on maximising value with the option of investing in either a wind or a marine project would tend to favour the wind project based on an analysis of the relative NPVs.

One further point worth noting is the relatively poorer performance of onshore versus offshore wind even in the earlier years when it might be anticipated that the more mature onshore wind technologies would deliver better economics (see Figures 4.55 to 4.56). A number of factors feed into this but principal among them is the different levels of support accorded to the two technologies once again highlighting the critical influence of policy support in this sector. More importantly, this would suggest that if support is not set at the "right" level, there would be a migration away from projects having better underlying fundamentals towards those having "abnormally" high policy support but which ultimately might not provide the optimal economic solution.

Turning attention to the results of the sensitivity analysis, it is interesting to note that relatively fewer of the input variables tested have an influence on the output results, reflecting the more homogeneous nature of the electricity generating plant being considered (see Figures 4.63 and 4.64). This is also reflected in the scenario analysis where, unlike in the case of hydrogen plant, relatively little variation across the scenarios is registered. One of the reasons for this is that in the case of hydrogen there is a first order effect from changes in the fossil fuel price. In the case of electricity, on the other hand, there is currently only a second order effect since the electricity and oil price are linked through the natural gas price as described in Section 2.5.7. However, with a move to more renewables it is reasonable to expect that this linkage would diminish and the therefore the effect is not modelled by the author since the model is primarily concerned with renewable electricity. Once again, the probability-weighted sensitivity analysis provides a useful distillation of the results (see Figures 4.65 to 4.71).

One further analytical approach employed is to consider the impact on the performance of different plant variants, both hydrogen and electricity, according to changes in paired input variables. Figures 4.75 to 4.86 show the variation in NPV as the electricity and petrol price are varied while Figures 4.88 to 4.97 consider the change in NPV with cost of capital and TOC price plus fuel duty benefit. While a useful way to view the combined effect of key variables, the principal interest of these charts is in allowing a comparison between hydrogen and electricity plant as variables significant to each is varied. Thus the petrol price is of importance to the hydrogen plant NPV while the electricity price is a key input to the electricity plant NPV. By comparing the relative NPVs as these inputs are varied it is possible to observe the effect of the price differential, likely to be of significant interest to an electricity utility considering an investment in hydrogen technologies. Similarly, if the relative changes in NPV can be observed as the level of RO and RTFO support is changed it is possible to analyse how these incentives interact as electricity and transport fuel converge.

Figures 4.87 and 4.98 provide the comparative data and demonstrate that while the economics of the electricity plant are generally better, under certain conditions favourable to the development of hydrogen energy, the NPV of hydrogen projects are higher than for electricity projects. Most notable is the case where the price of petrol is high, reflecting a high oil price (and ignoring any second order effect on the electricity price as a result). However, across a broad spectrum of analysis this is not the case, weakening the case for investment in hydrogen infrastructure where the choice is between that and investment in electricity plant. What emerges from this analysis is that as the boundaries between different energy “silos” begin to blur and electricity, for example, is increasingly directed towards transport either through hydrogen or directly, so the different incentives increasingly overlap. Thus while up to now the RO and RTFO have been developed, and the effects analysed, independently, these two policy instruments may now overlap and may possibly result in counter incentives. It can be seen from the analysis that setting support levels for electricity generation, say, too high may result in a deleterious effect on efforts to support other technologies such as hydrogen.

To summarise, this chapter discussed:

- The way in which the initial analyses would be presented was described and explained; these methods were General Analysis, Sensitivity Analysis, Probability weighted Sensitivity Analysis, Scenario Analysis and Comparative Analysis. In each case any relevant equations were set out.

- The hydrogen and electricity plant results were presented and discussed highlighting the overall patterns for the variation in NPV, revenues and profits

- The variables to which the outputs were most sensitive were identified and the reasons for this were discussed

- The performance of these different plant was considered in each of the four scenarios detailed in Figure 4.2

- The relative value performance of projects in the hydrogen and electricity domain were considered and compared. These were compared over variations in relative electricity and petrol price and cost of capital and policy measures.

- The issues associated with policy setting and the creation of conflicting incentives was discussed.

# 5 Discussion of Implications for the Model

In Sections 4.2 and 4.3 possible outcomes in absolute terms with respect to the different plant types analysed in this study were explored as a means to creating a baseline set of scenarios. Meanwhile, in Section 4.4 the relative economics were discussed in relation to changes in different input variables, especially those related to price and policy. This provided a set of benchmarks and information regarding aspects such as the relative sensitivity of the model to different input data but the principle theme of this research is to gain an understanding of the propensity for companies to invest in hydrogen and fuel cell technology and to create a forecast based on that investment proposition. Thus, in this Chapter the findings from Chapter 0 are integrated with the actual performance of companies in the sector. In Section 5.1 the specific impact on a range of potential market players of investing in hydrogen and fuel cell plant is examined in more detail with a view to understanding the likelihood that these companies would consider an investment in the sector. Section 5.2 discusses the potential implications of combining renewable and hydrogen investments for electricity utilities while finally Section 5.3 pulls together all these themes to offer an overall set of forecasts for market development.

## *5.1 Company Specific Analysis*

As was discussed in Section 3.6.3.4, of particular interest to this analysis is the performance of companies that might look to develop hydrogen and / or renewable energy projects in the future. Needless to say, it is impossible to predict which companies currently in existence would want to develop their activities in the area of hydrogen energy in the future. Even more uncertain is the question of what characteristics new companies not yet in existence might demonstrate. However, it is possible to imagine certain categories of company that might reasonably be expected to have an interest in the sector and historical performance, financial and returns data pertaining to three such groups were presented in Table 3.21 of Section 3.6.4.2.

These companies fall into three distinct categories namely, electricity and gas utilities, oil and gas majors and industrial gases companies, and Table 3.21 from Section 3.6.4.2 is reproduced here for ease of reference (Table 5.1). Regarding possible new entrants, it is interesting to speculate whether they might eventually sit within one of these such categories and whether, if this was the case, that they would then come to display similar fundamental characteristics. Additionally, it may be anticipated that if historical paradigms for the delivery and use of energy are to be fundamentally disrupted, the valuation and performance characteristics of companies in the sector might fundamentally change as well. While an interesting discussion, further analysis is beyond the scope of this Thesis and it is assumed that all companies acting in the sector would have characteristics bounded by those companies acting in the sectors described.

For each company, plant type and core reference years (2015, 2025 and 2035), the valuation measures (NPV, Year-10 Revenue and Yer-10 Profit) are calculated for each of the scenarios used in the Monte Carlo analysis. An example of the output for the SUS case is shown in Table 5.2. The NPV data is presented as is, whereas the EPS data is presented as a percentage accretion or dilution figure, and the multiples data as an implied share price. The reason for doing this is to present the data in a way that can be more satisfactorily compared.

Company Performance and Valuation Data

*All amounts in GBP million unless otherwise stated*

| | Utilities | | | | | | Oil and Gas | | | Industrial Gases | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Name** | **Iberdrola** | **Iberdrola Renovables** | **SSE** | **Centrica** | **Drax** | **Intern'l Power** | **BP** | **Shell** | **BG** | **Air Products** | **Solvay** | **BASF** | **Air Liquide** |
| LTM Revenues | 23,629.5 | 1,756.7 | 24,278.6 | 21,345.0 | 1,657.9 | 3,821.0 | 141,573.3 | 277,794.5 | 10,862.0 | 5,358.5 | 7,660.9 | 45,065.2 | 11,017.5 |
| *LTM Growth (%)* | *14%* | *23%* | *29%* | *31%* | *18%* | *64%* | *-40%* | *128%* | *-8%* | *-10%* | *-19%* | *-57%* | *1%* |
| LTM EBIT | 3,664.9 | 560.5 | 1,899.7 | 1,942.0 | 347.0 | 1,156.0 | 9,593.3 | 30,964.2 | 4,130.0 | 540.2 | 646.1 | 2,576.5 | 1,615.5 |
| *EBIT Margin (%)* | *16%* | *32%* | *8%* | *9%* | *21%* | *30%* | *7%* | *11%* | *38%* | *10%* | *8%* | *6%* | *15%* |
| LTM Earnings | 2,094.1 | 284.4 | 1,163.6 | 903.0 | 238.2 | 667.0 | 5,417.6 | 15,946.1 | 2,482.0 | 393.3 | 207.0 | 558.3 | 759.1 |
| *Net Margin (%)* | *9%* | *16%* | *5%* | *4%* | *14%* | *17%* | *4%* | *6%* | *23%* | *7%* | *3%* | *1%* | *7%* |
| Historic Earnings Per Share (pence) | 42.8 | 6.7 | 126.1 | 21.3 | 70.0 | 39.2 | 28.5 | 258.4 | 73.9 | 184.8 | 251.0 | 60.8 | 287.3 |
| Historic Dividend Per Share (pence) | | | | | | | | | | | | | |
| Fully Diluted Shares Outstanding (million) | 4,894.9 | 4,223.4 | 922.9 | 4,233.0 | 340.4 | 1,702.1 | 18,987.0 | 6,171 | 3,360 | 212.8 | 82.4 | 918.5 | 264.3 |
| Cash | 1,814.4 | 218.3 | 711.4 | 2,939.0 | 164.6 | 1,129.0 | 5,989.7 | 9,205 | 664 | 42.6 | 500.0 | 2,548.7 | 1,119.8 |
| Long Term Debt | 20,060.1 | 3,185.7 | 4,816.7 | 3,218.0 | 319.0 | 7,026.0 | 16,404.8 | 8,347 | 3,096 | 2,276.2 | 1,360.9 | 12,441.0 | 5,395.8 |
| Book Value of Liabilities | | | | | | | | | | | | | |
| Cost of Debt | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% | 6.0% |
| Market Return (%) | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% | 10.0% |
| Risk Free Rate | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% | 4.0% |
| CAPM | 9.7% | 10.8% | 7.8% | 7.3% | 7.5% | 9.4% | 7.8% | 7.9% | 8.4% | 8.3% | 8.2% | 10.4% | 9.3% |
| WACC Based on 70:30 Equity:Debt split) | 8.6% | 9.3% | 7.3% | 6.9% | 7.1% | 8.4% | 7.3% | 7.3% | 7.7% | 7.6% | 7.6% | 9.1% | 8.3% |
| Share Price (average last 90 days in pence) | 546.0 | 287.2 | 1,115.3 | 241.98 | 456.05 | 270.27 | 525.9 | 1,531.5 | 1,073.9 | 5,087.0 | 6,024.4 | 3,112.5 | 6,678.8 |
| Market Capitalisation | 26,725.0 | 12,130.5 | 10,293.3 | 10,242.9 | 1,552.4 | 4,600.2 | 99,855.0 | 94,508.9 | 36,084.2 | 10,825.2 | 4,967.0 | 28,588.1 | 17,649.1 |
| Enterprise Value | 44,970.7 | 15,097.9 | 14,398.6 | 10,521.9 | 1,706.8 | 10,497.2 | 110,270.2 | 93,650.7 | 38,516.2 | 13,058.8 | 5,827.8 | 38,480.4 | 21,925.1 |
| Ratio Debt / EV (%) | 45% | 21% | 33% | 31% | 19% | 67% | 15% | 9% | 8% | 17% | 23% | 32% | 25% |
| Ratio Debt / Equity (%) | 75% | 26% | 47% | 31% | 21% | 153% | 16% | 9% | 9% | 21% | 27% | 44% | 31% |
| Enterprise Value / Revenues | 1.9 | 8.6 | 0.6 | 0.5 | 1.0 | 2.7 | 0.8 | 0.3 | 3.5 | 2.4 | 0.8 | 0.9 | 2.0 |
| Enterprise Value / EBIT | 12.3 | 26.9 | 7.6 | 5.4 | 4.9 | 9.1 | 11.5 | 3.0 | 9.3 | 24.2 | 9.0 | 14.9 | 13.6 |
| Price / Earnings | 12.8 | 42.7 | 8.8 | 11.3 | 6.5 | 6.9 | 18.4 | 5.9 | 14.5 | 27.5 | 24.0 | 51.2 | 23.2 |

**Table 5.1 Performance, Balance Sheet and Valuation Indicators Relating to the 13 Energy Companies**

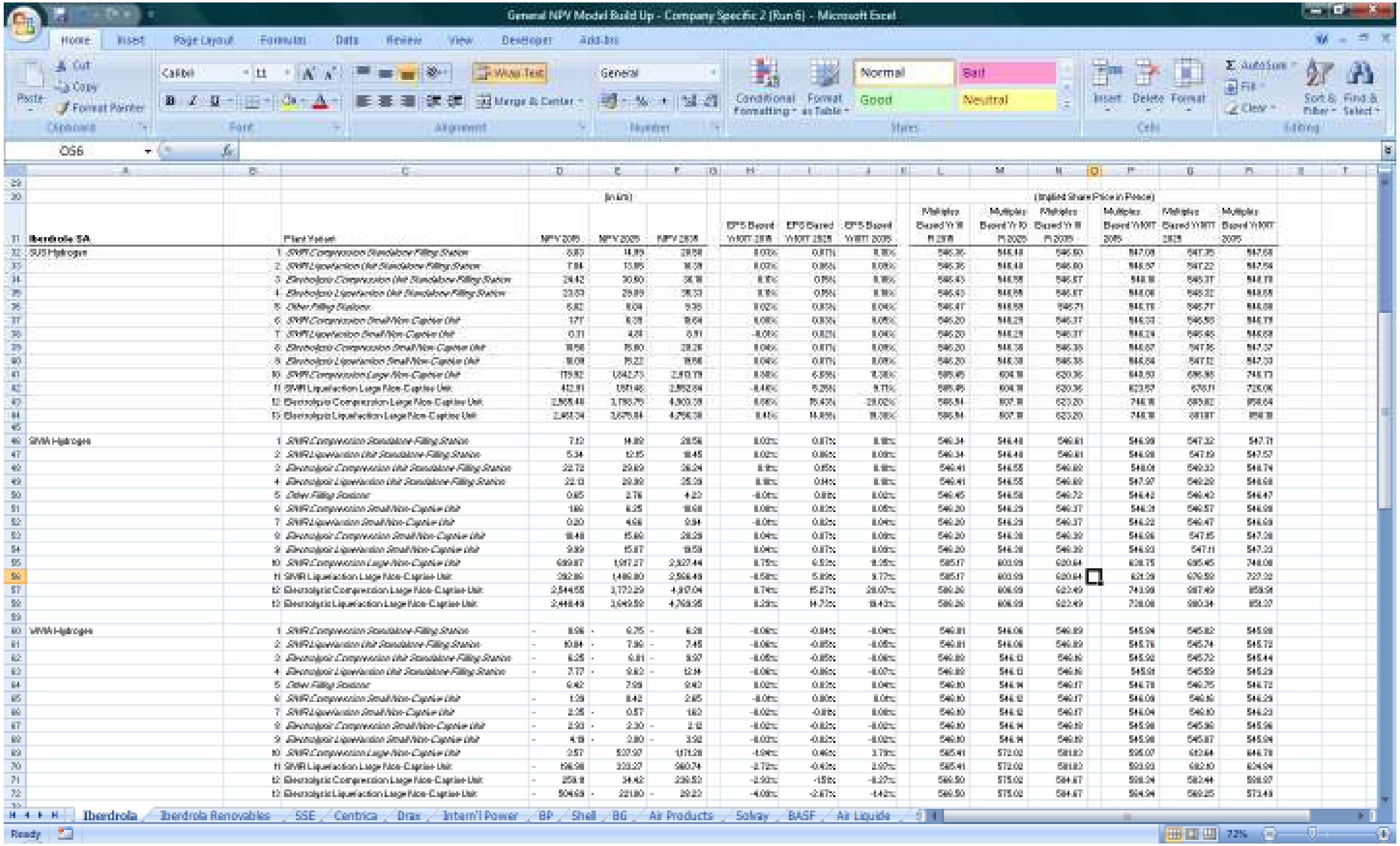



Table 5.2 Screenshot of an Output Worksheet from the Company Specific Analysis

### 5.1.1 Propensity for Certain Companies to Invest

Since each company has different financial characteristics it is worthwhile analysing whether certain companies would have more of a propensity to invest in hydrogen production infrastructure than others. By way of example, Figure 5.1 shows the variation in NPV over each of the four scenarios in the 2025 reference year and for each company for the small natural gas fuelled hydrogen refuelling plant (RNGC).

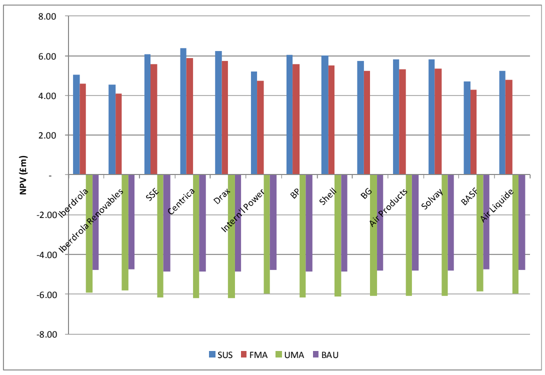



**Figure 5.1 NPV Analysis of Small Scale RNGC by Company and Scenario**

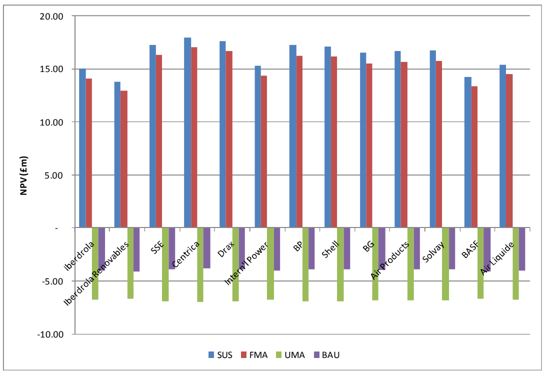



**Figure 5.2 NPV Analysis of Large Scale RNGC by Company and Scenario**

The variability of NPV according to scenario is similar to that observed previously in the scenario analysis (see Sections 4.1.4 and 4.2.3) with a clear bifurcation between the SUS and FMA cases and the UMA and BAU cases. Variability of NPV according to company is relatively modest and reflects the variation in discount rate apparent between the different companies; this discount rate varies between fairly close bounds. Figure 5.2 shows the results for the larger version of the same plant type with very similar results.

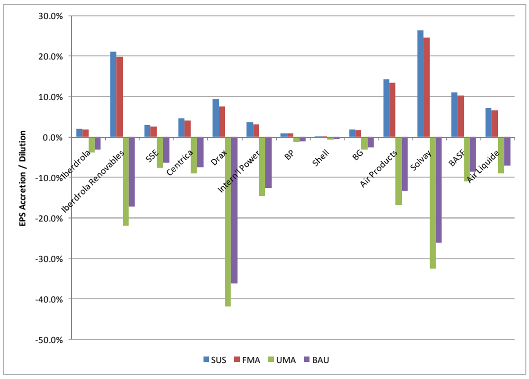



**Figure 5.3 EPS Analysis of Small Scale RNGC by Company and Scenario**

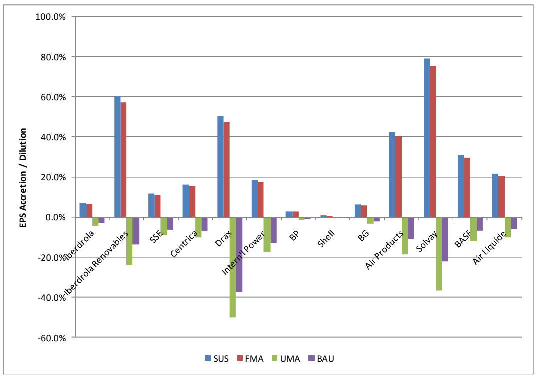



**Figure 5.4 EPS Analysis of Large Scale RNGC by Company and Scenario**

When the EPS statistics are considered, the variability between companies is seen to be considerably more marked reflecting two key factors. The first is the size of the project relative to the size of the company itself with the impact of the new project clearly being greater on smaller companies than on larger ones. The second factor is the existing level of EPS for the company which in turn reflects the relative profitability and its share price. Figures 5.3 and 5.4 present the results for the small and large RNGC plants as previously; because the plant projects are relatively small in size, multiples of 100 plant are considered here in order to better visualise the effects. What Figures 5.3 and 5.4 serve to indicate is that if the primary driver for companies considering an investment in hydrogen and fuel cell infrastructure is the possible impact that such investment might have on EPS, then a relatively wide range of possible outcomes might be expected from that decision-making process. However, it is important to recognise the limitations of this comparison. For example, it would be wrong to infer based solely on this data that because the impact on Shell's EPS of investing in the RGNC plant is rather small, Shell would be unlikely to invest in this technology since the modest impact is largely a reflection of Shell's considerable size. Conversely, those companies for which the EPS impact is high might not necessarily consider an investment to be attractive if the risk profile of the project was considered inappropriate.

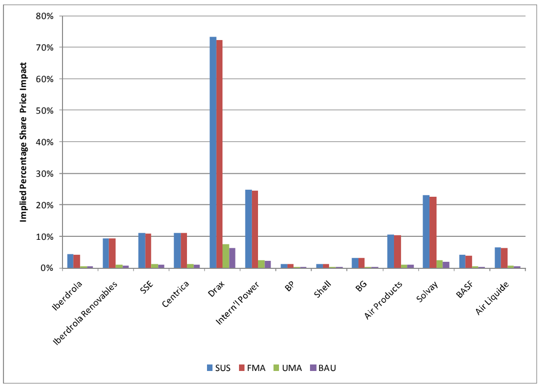



**Figure 5.5 Revenue Multiple Analysis of Small Scale RNGC by Company and Scenario**

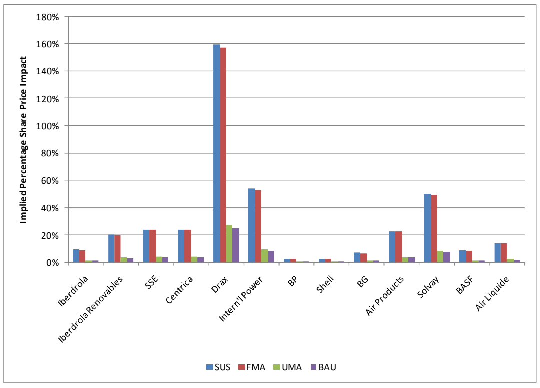



**Figure 5.6 Revenue Multiple Analysis of Large Scale RNGC by Company and Scenario**

Figures 5.5 and 5.6 present the valuation data derived from the revenue multiple analysis. Since the projects are taken to be purely additive, that is they are not made at the expense of any other investment, the impact on value is always positive since in this model the projects always generate revenue. However, if these projects were seen to be a substitute for the company's "normal" investments which underpin the historical growth of its "traditional" business it would be necessary to compare the relative growth and profitability trajectories. Since little information is available regarding the capital capacity of the firms under consideration such an analysis is not presented here; it could, however, be incorporated into further research. The relative impact is driven by the relative size as measured by the enterprise value of each of the companies under consideration.

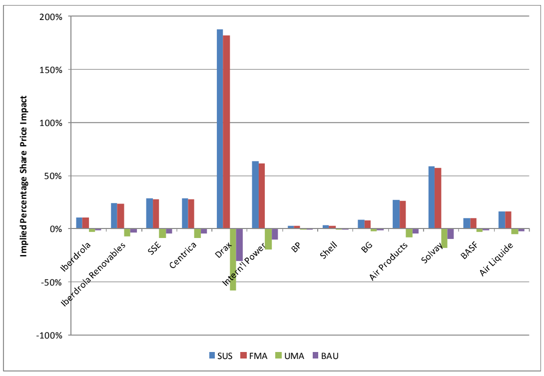



**Figure 5.7 Earnings Multiple Analysis of Small Scale RNGC by Company and Scenario**

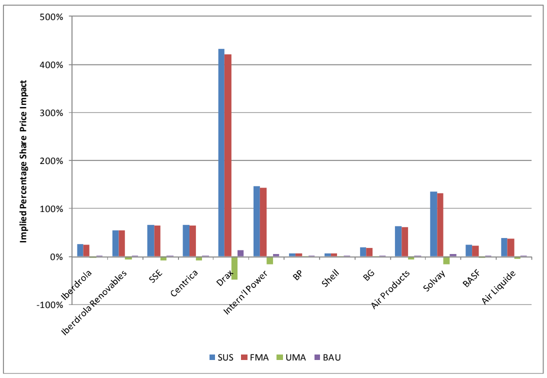



**Figure 5.8 Earnings Multiple Analysis of Large Scale RNGC by Company and Scenario**

The final set of results assesses the value impact based on earnings multiples (Figures 5.7 and 5.8). It can be seen that, unlike in the case of the revenue-based multiples, the impact of making the investment can be both positive and negative depending on whether the project is profitable or loss-making. Note that in the case that the project was consistently profitable the same comments as were made for the revenue analysis would apply. Once again the relative impact here is driven by the relative size but as measured by the market capitalisation rather than the enterprise value.

Attention is now turned to comparing the relative performance of two example plants, the mid-sized electrolysis compression multi-purpose unit and the small scale onshore wind generation plant in continuation of the analysis made in Section 4.4. Figures 5.9 to 5.12 present the NPV, EPS and multiples based value data for the two plant types in the SUS and UMA cases. The key point to note is the relatively higher variability between the two cases observed for the hydrogen plant as compared with the electricity generation plant. For example, in absolute terms the NPV of the hydrogen plant is considerably higher than for the generation plant in the SUS case whereas in the UMA case the NPV is negative. By contrast, the generation plant shows a positive NPV in both cases. The relatively greater variation in the case of hydrogen plant is confirmed through the other measures used.

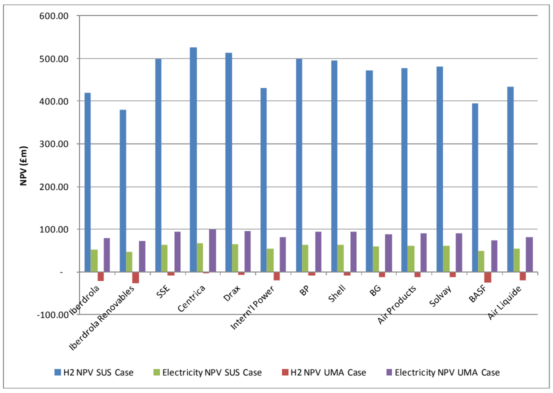



**Figure 5.9 Relative $H_2$ and Electricity Plant NPV Scenario Analysis for SUS and UMA Cases and Company**

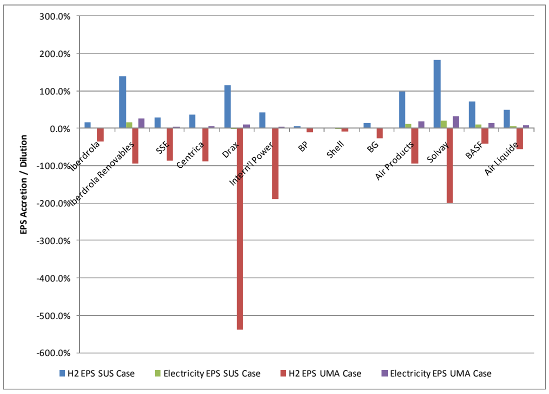



**Figure 5.10 Relative $H_2$ and Electricity Plant EPS Scenario Analysis for SUS and UMA Cases and Company**

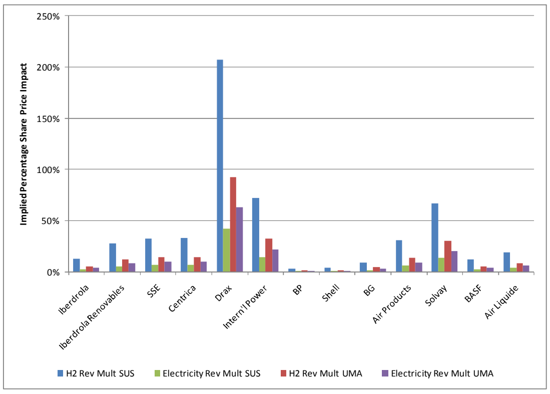



**Figure 5.11 Relative Hydrogen and Electricity Plant Revenue Multiple Scenario Analysis for SUS and UMA Cases and Company**

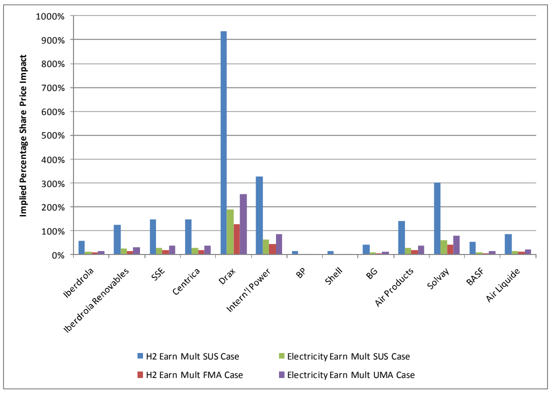



**Figure 5.12 Relative hydrogen and Electricity Plant Earnings Multiple Scenario Analysis for SUS and UMA Cases and Company**

Examination of these variable effects has important implications for the development of policy instruments which must try to incentivise as broad a base of companies as possible.

## *5.2 Examination of Combinatory Effects*

The relative economic benefit of a combined investment in hydrogen energy infrastructure and electrical generation capacity is a useful analysis but complex and perhaps best examined in the context of a specific example.

### 5.2.1 Physical Description and Key Assumptions

The example model proposed describes an opportunity for an existing electric utility that generates and supplies traditional fossil-based and renewable energy, to develop a new large-scale wind farm in the Shetland Islands (see Figure 5.13). Since the wind farm is in a location where no grid connection currently exists, the utility wishes to compare the relative economics of building a new grid connection and selling electricity into the pool or building hydrogen production capacity and shipping liquid hydrogen in bulk carriers from the modified existing deep-water oil terminal for sale as transport fuel for hydrogen fuel cell vehicles.

While Liquid hydrogen bulk carriers do not currently exist, for the purposes of this analysis the technology is assumed to have reached a reasonable level of maturity with the basic technical assumptions being based around existing bulk LNG carriers.

Four potential options are explored in the analysis and are shown schematically in Figure 5.13. These are described as follows:

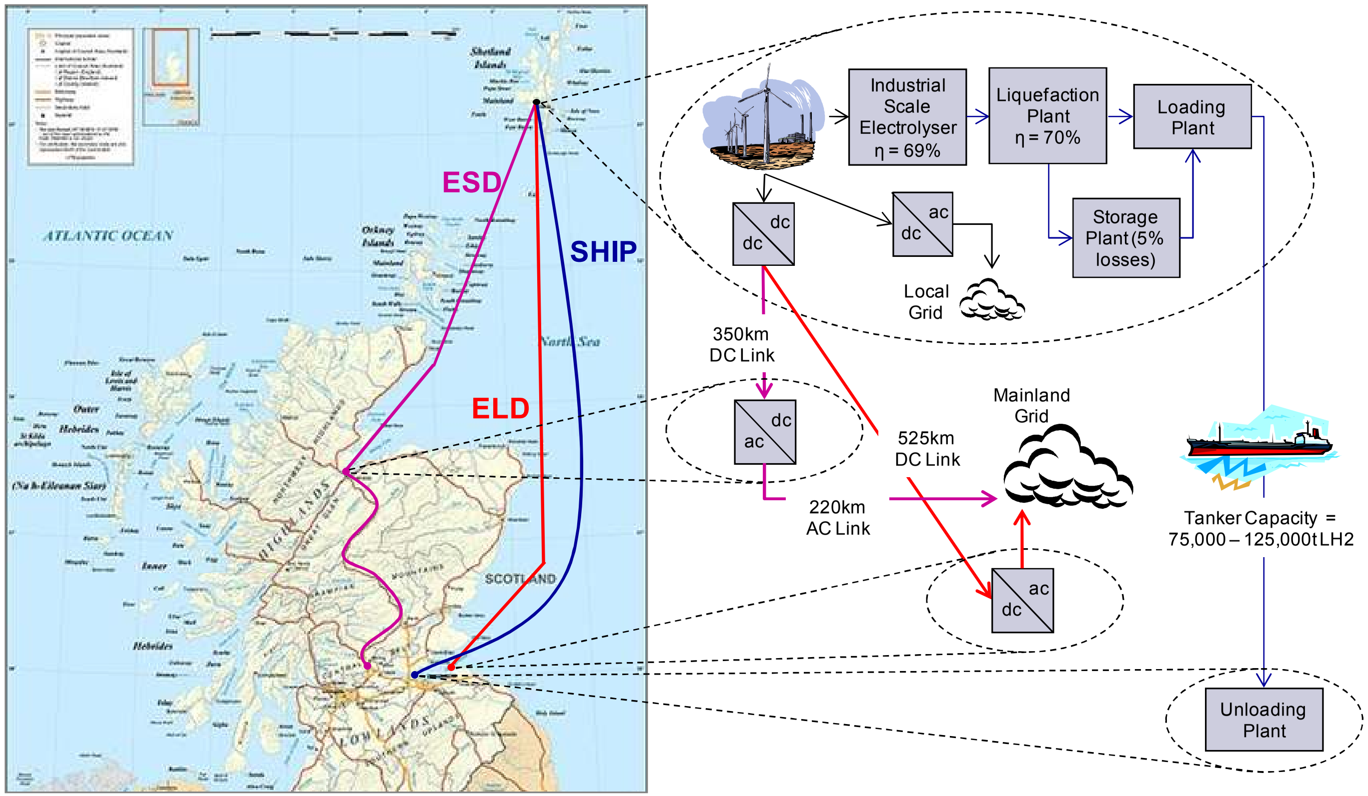
***Hydrogen Only (HFO)*** – All electricity is converted to hydrogen which is then liquefied and shipped from the Islands in $LH_2$ tankers for distribution on the mainland.

***Hydrogen Plus Local Electricity (HLE)*** – A proportion of electricity is directed towards the local independent grid within the archipelago.

***Electricity to new grid via short DC link to mainland (ESD)*** – The archipelago is connected to the mainland via a "short" DC link where it is then connected to a new / upgraded ac grid network.

***Electricity to grid via long DC link to mainland (ELD)*** – The archipelago is connected to the mainland grid via a "long" DC link to the Central Belt of Scotland.

The plant and market characteristics follow those described elsewhere in this Thesis including the relative prices of different energy types, which are determined with reference to existing prices and relative system efficiencies. An important aspect of this is that the entire benefit of improved efficiency at the application level (i.e. the vehicle level) accrues to the supplier. In other words, if it is assumed that a fuel cell vehicle is, say, twice as efficient as a petrol internal combustion engined vehicle then it is assumed that the consumer would be prepared to pay twice as much per unit of input energy as the fuel consumption obtained is halved. In perfectly competitive markets it might be assumed that the efficiency improvements would be shared in some proportion between the supplier and the consumer so this simplification requires some caution.




**Four cases are considered:**

***Hydrogen Only (HFO)*** – All electricity converted to hydrogen which is liquefied and shipped from the Islands in LH2 tankers for distribution on mainland.

***Hydrogen Plus Local Electricity (HLE)*** – Proportion of electricity directed towards local independent grid within the archipelago.

***Electricity to new grid via short DC link to mainland (ESD)*** – Archipelago is connected to mainland via a "short" DC link where it is connected to new ac grid.

***Electricity to grid via long DC link to mainland (ELD)*** – Archipelago connected to the mainland grid via a "long" DC link to the Central Belt.

**Figure 5.13 Schematic Representation of Physical Systems in the Shetland Wind Farm Model**

For the purposes of analysing the impact on value, Scottish Power is chosen as the potential developer of the project since the company is a collaborator with the author on this research. Company performance and share price data for Scottish Power prior to the merger with Iberdrola (the Spanish utilities group) is utilised and presented in Table 5.3. It was considered possible to utilise either Iberdrola or Iberdrola Renovables data to provide the benchmark but the effects can be less easily seen with reference to the much larger Iberdrola and the amount of historical data pertaining to Iberdrola Renovables is limited. In any case, the example is intended to be illustrative of the possible effects of considering the investment from different perspectives.

| **Share Parameters** | **Value** | **Performance Parameters** | **Value** |
|---|---|---|---|
| Share Price at 15 May 2006 (pence) | 553.0 | LTM Revenues (£m) | 5,446.1 |
| Number of Shares Out | 1,871.2 | LTM Earnings (£m) | 813.5 |
| Long term Debt (£m) | 3,079.4 | Revenue Growth | *13%* |
| Cash (£m) | 200.0 | EPS (pence) | 43.5 |
| EV / R | 2.43 | EPS Growth | *14%* |

*EV = Enterprise Value = Equity Market Capitalisation + Long Term Debt – Cash*
*R = Revenues*

*LTM = Last Twelve Months (i.e. the 12 months prior to 15 may 2006)*
*Source: Yahoo! Finance, Company reports*

**Table 5.3 ScottishPower Performance, Balance Sheet and Valuation Data**

The industry sector EV/R multiples are those presented previously in Table 3.21 and only the revenue multiple is considered since most of the new energy companies are pre-profitability.

### 5.2.2 Model Outputs

The variation of each of the three value-related measures is calculated while three key chosen input parameters, namely price, cost of capital and EV / R multiple are varied.

Figure 5.14 provides an overview of the NPV for each project scenario as the energy price is varied. The NPV for the electricity only projects (ELD and ESD) is always higher on a like-for-like price basis although, as could be anticipated, for hydrogen prices (determined with reference to the petrol price) at the upper end of the range, the NPV of the HFO and HLE scenarios does exceed the electricity base case. Figure 5.15 plots the ratio of the hydrogen price to the electricity price for equal NPVs across the range modelled. As can be seen, in the limit a hydrogen-to-electricity price ratio of roughly 2x would render equal NPVs for the hydrogen and electricity scenarios.

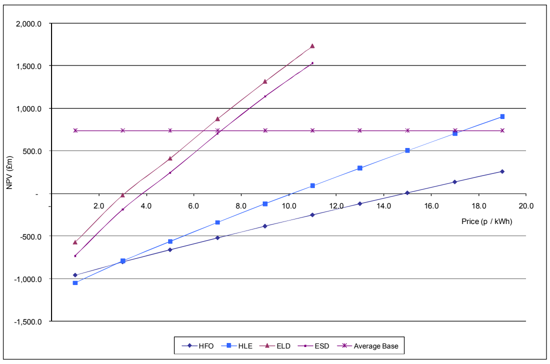



**Figure 5.14 Variation of NPV of Hydrogen and Electricity Projects with Electricity ($P_e$) and Hydrogen ($P_h$) Price**

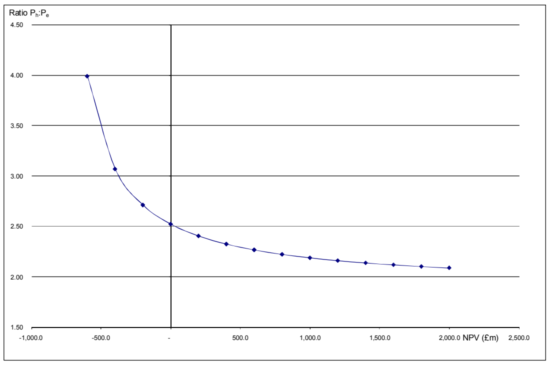



**Figure 5.15 Ratio of ($P_h$) to ($P_e$) for Equal NPV**

Figures 5.16 and 5.17 present the variation in NPV for one each of the hydrogen (HFO) and electricity (ELD) cases as the cost of capital and price are varied. Each line represents either an iso-hydrogen or iso-electricity-price curve, with the lower limit corresponding to a price of 1p per kWh and the upper limit 19p per kWh. The results confirm the findings shown in Figure 5.14 regarding the overall level of NPV but also serve to highlight the fact that, over the range of discount rates modelled, the effect of discount rate is subordinated to that of price. Nevertheless, at the margin a different choice of discount rate for one or other type of project would affect the ranking of the projects by NPV.

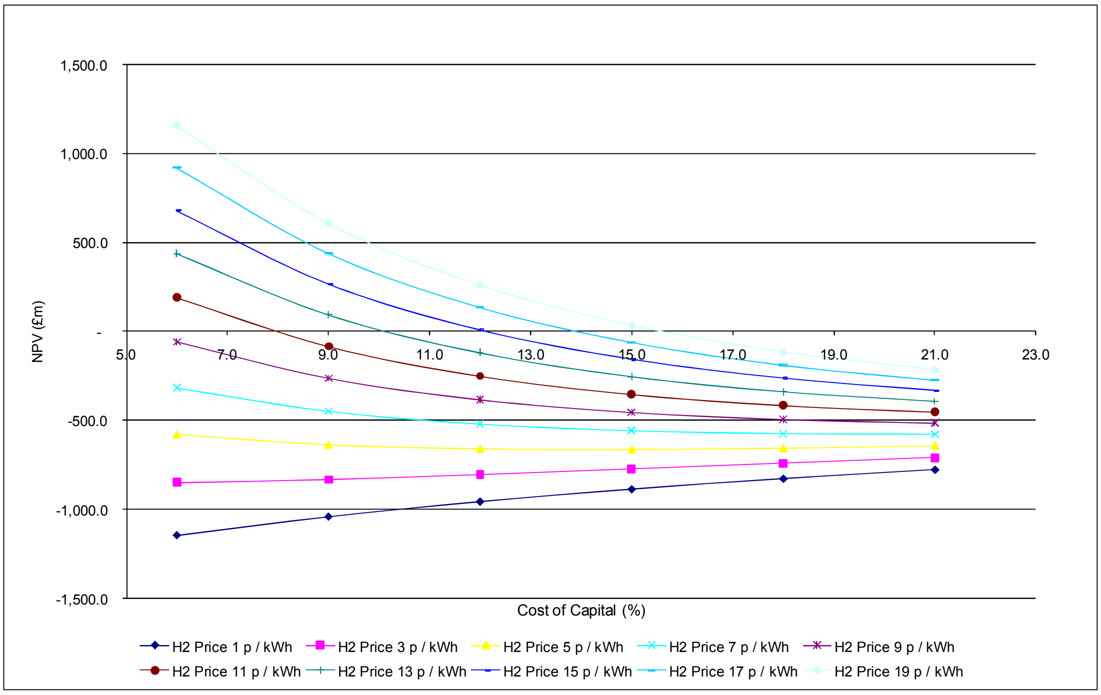



**Figure 5.16 Variation of NPV with Hydrogen Price and Cost of Capital for HFO Scenario**

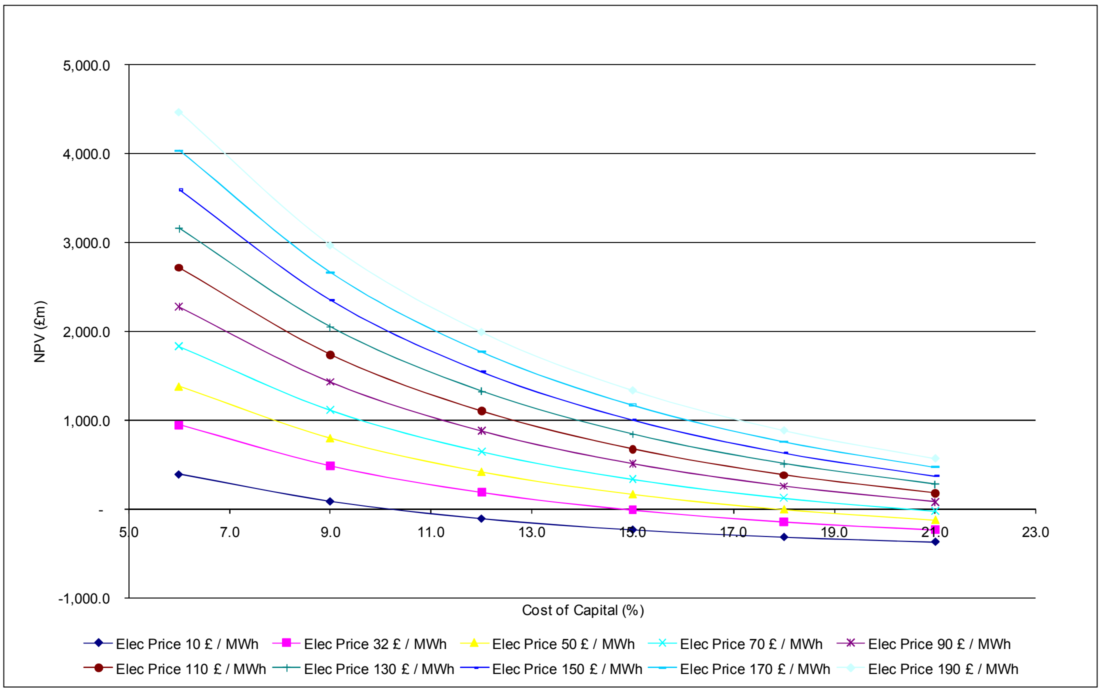
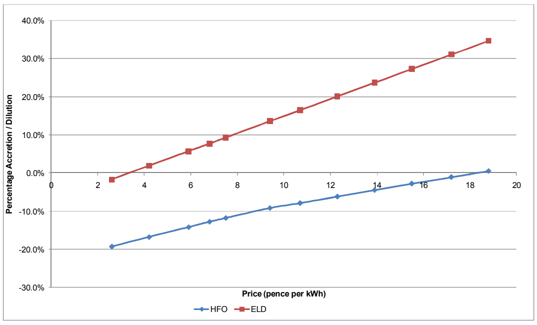
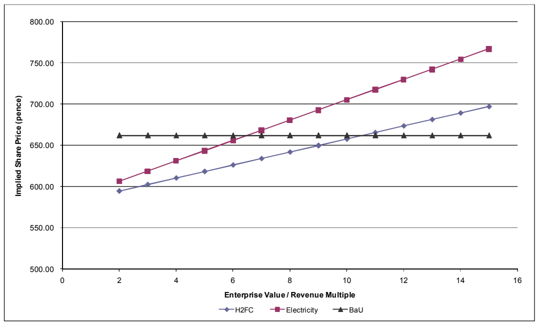



**Figure 5.17 Variation of NPV with Electricity Price and Cost of Capital for ELD Scenario**

Figure 5.18 shows the EPS impact across the range of prices in year 10 of the operation of the plant. As with the NPV cases, the EPS impact of the electricity project is higher than for the hydrogen projects on an equivalent price basis, i.e. like-for-like price points. In contrast to the base case NPV for the HFO scenario which is slightly positive, the EPS effect at the base case price is negative; the ELD scenario on the other hand is slightly positive. The HFO case is earnings neutral at around 18p per kWh, in the upper end of the range, while ELD is earnings neutral at around 3p per kWh, around the base case price.




*Note: Business as usual case assumes continued growth at historic levels*

**Figure 5.18 Variation in Year 10 EPS from HFO and ELD Projects with Change in $P_h$ and $P_e$**

**Figure 5.19 Value Impact of HFO and ELD Cases According to EVR Multiple Based on Year 10 Revenue**

Until the middle of 2009, the multiple-based valuation impact analysis has proved particularly interesting since a significant valuation differential existed between the hydrogen and fuel cell companies and those in the other sectors analysed. The impact on value of "hydrogen revenues" was therefore disproportionately higher than for the electricity case. However, in since then until the time of writing (early 2010) there has been a dramatic decline in the multiples for almost all alternative energy sector companies and hydrogen and fuel cell companies have been particularly hard hit seeing EV / R multiples decline from a high of roughly 12x in 2007 to 4.3x in 17 November 2009. Multiples in the $H_2$FC sector are now scarcely higher than for traditional energy sectors suggesting that previous investor belief in the potential for the sector has significantly diminished and hence weakening the argument for investing in the $H_2FC$ sector in order to benefit from valuation differentials (and the underlying benefits that are implied). Figure 5.19 presents the range of implied share price across different multiples for the HFO and ELD cases, based on year 10 revenues. Compared to the business as usual case, a multiple of 11x would be share price neutral for the HFO case and roughly 6x for the ELD case.

### 5.2.3 Price Arbitrage Opportunity

To date electricity utilities have confined their activities to the supply of electrical power to domestic, commercial and industrial consumers. If, as is the case within a the partially "controlled" electricity market "silo", all suppliers must submit to a single price and growth is limited [153], it might be argued that a cost minimisation strategy would yield the highest after tax receipts and, according to the neo-classical approach [15], this would also maximise returns as discussed in Section 2.6.5. However, the production of hydrogen fuel from fossil or non-fossil based electricity could open up new market opportunities for utilities by crossing over from the electricity "silo" to the transport fuels "silo". This not only presents opportunities for growth as has been discussed in Section 5.2.2 but also offers the prospect of benefiting from price arbitrage opportunities that might exist between different energy "silos". By way of illustration, reference to Figure 2.14, which provides temporal data for energy prices, highlights the potential for price arbitrage which an electricity utility might seek to exploit. The relationship between the price movements of different energy types can be examined with reference to the correlation coefficient defined by Equation (5.1) [154].

$$Correl(X,Y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) \times (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad \textbf{(5.1)}$$

where

*Correl(X, Y)* = the correlation coefficient between two arrays, X and Y

$x_i$ = the $i^{th}$ value of n in the array X

$\bar{x}$ = the sample mean of X

$x_i$ = the $i^{th}$ value of n in the array Y

$\bar{y}$ = the sample mean of Y

The correlation coefficient between the transport fuel and electricity price indicates a degree of counter-cyclicality although the relationship to the crude oil price has traditionally been stronger owing to amongst other things the natural gas effect (see Section 2.5.7). Over the time period presented, the electricity price appears to be closely correlated with a time lag of approximately 3 months and if the time lag is removed then the correlation coefficient is revealed to be 0.65 (relatively high, with 1 being perfectly correlated, 0 completely uncorrelated and -1 perfectly inversely correlated). However, during the last year there appears to have been a greater disparity in behaviour and this is confirmed by looking at the correlation coefficients for the periods up to March 2009 (time lagged correlation of 0.69) and since March 2009 where the correlation has actually turned negative for raw pricing data (-0.51) and around zero once the previously identified lag has been removed (0.07). While the data is not conclusive there is nevertheless some reasonable evidence to assume that an electricity producer able to exploit both oil price and electricity price peaks may be able to maximise after tax receipts (and hence value). One way of taking account of this possibility in the model would be to adjust the discount rate to a lower value for the renewables plus hydrogen scenario to reflect the risk reduction implicit in such a strategy but a detailed discussion is beyond the scope of this Thesis.

### 5.2.4 Concluding Comments

While not designed to present a generalised analysis of the effects of combining investments in hydrogen and electricity this example goes some way to showing that in the case where the price of electricity and the price of hydrogen are decoupled, changes in one or another will affect the overall value of the investment choices. In certain instances it can be seen that the addition of hydrogen energy production can add value to a generation project. However, a number of limitations with the analysis are apparent not least of which is the fact that all the cost of the grid connection from Shetland to the mainland is born by the project developer, which may be considered unrealistic if it could be anticipated that other energy generation projects could be developed on the islands.

## 5.3 Completing the Forecast

Having explored each aspect of performance analysis in turn, this section is concerned with exploring and reconstructing a potential future forecast. In Chapter 3, one potential future demand scenario was described (see Figure 3.18) and is reproduced in Figure 5.20 by way of reference.

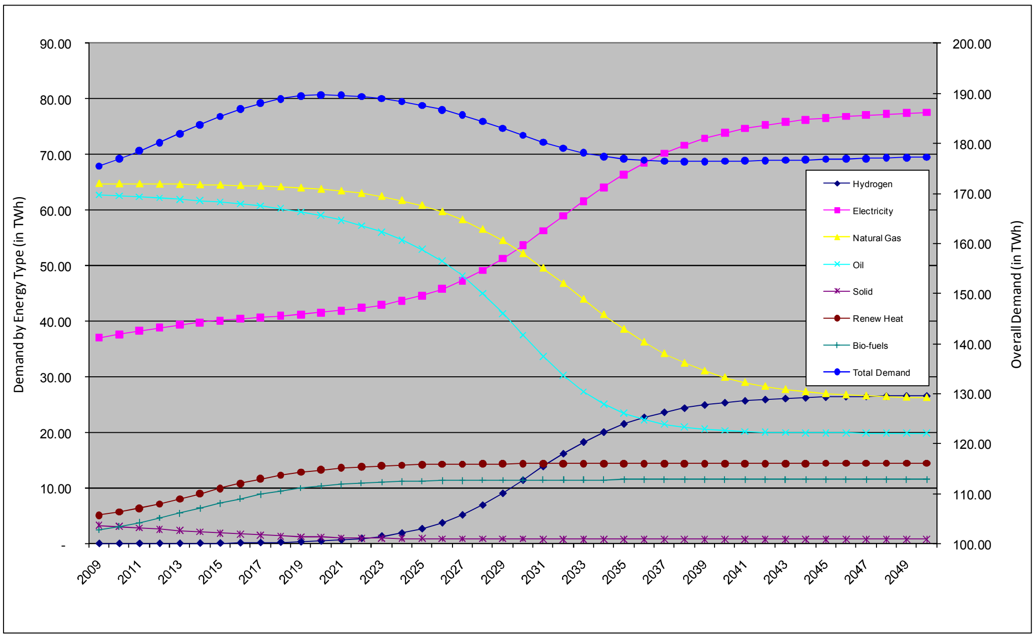



**Figure 5.20 Forecast Demand by Energy Type 2010 – 2050**

The model is then run in such a way as to reconstruct the capacity build up curves based on the viability of the different plant types in the period when they are due to be rolled out. If the plant is value additive then it will be rolled out, if not the demand remains unfulfilled. The model allows any number of different supply mixes to be investigated and two such mixes are presented; one favouring small decentralised units, where small scale on-site production predominates, and the other favouring large scale centralised production where production is concentrated in large plant and delivery is through a system of transport and delivery stations, much like today's transport fuel delivery infrastructure or gas supply networks. Once again, it should be emphasised that the initial scenario does not necessarily predetermine the outcome in terms of capacity build-up; for example, the initial scenario may be defined as centralised but if the model determines a preference for decentralised plant the “actual” capacity build-up would tend to favour the decentralised regime. The introduction of the different plant variants follows the demand curve for hydrogen from Figure 5.20 and the expected take up according to plant type in the initial scenarios is shown in Figures 5.21 and 5.22.

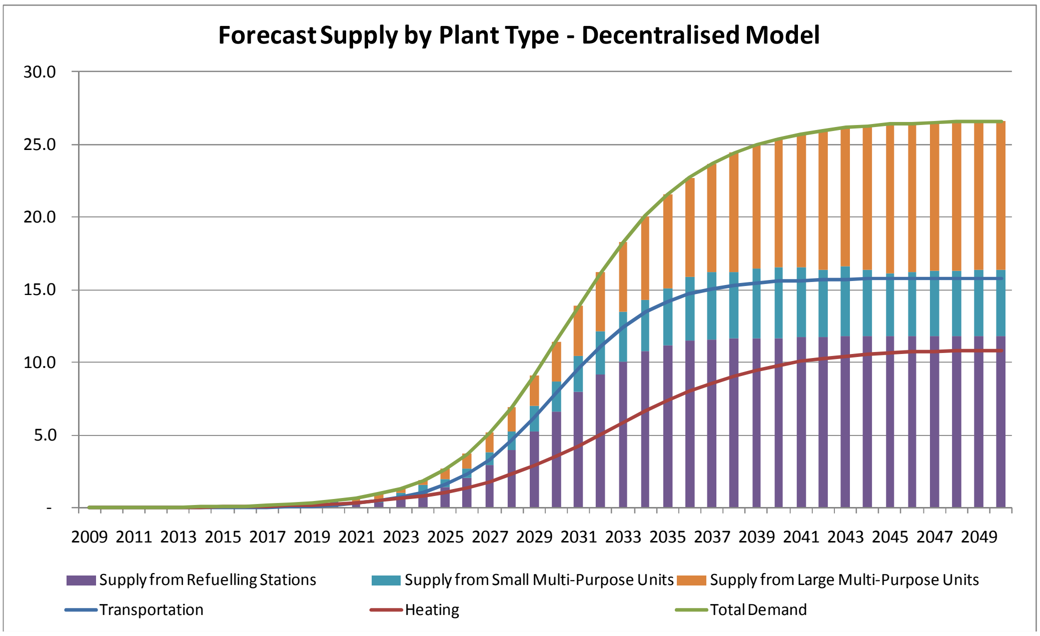



**Figure 5.21 Forecast Supply by Plant Type – Decentralised Case**

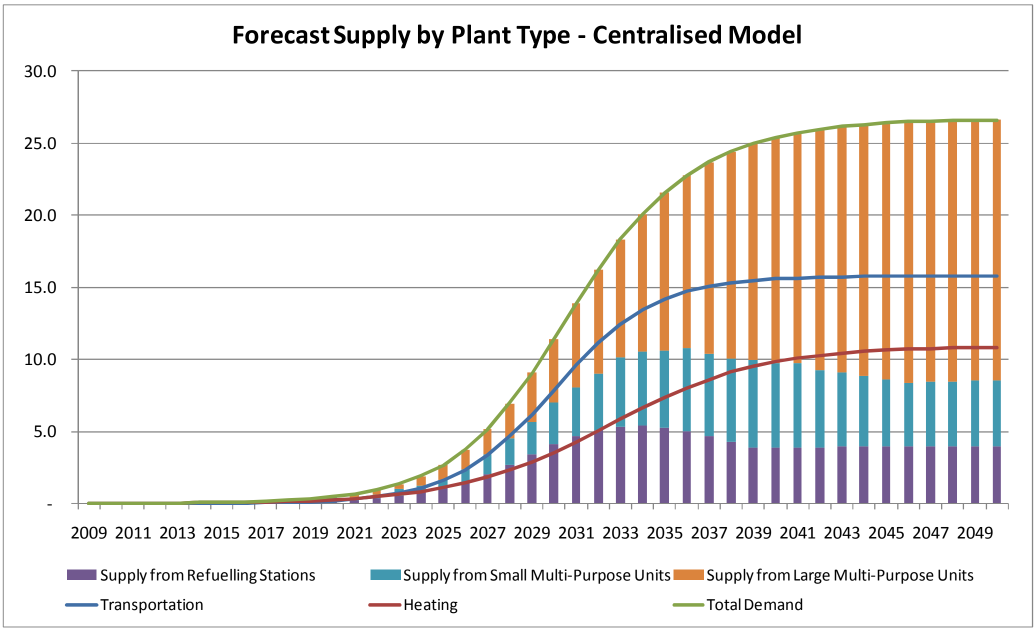



**Figure 5.22 Forecast Supply by Plant Type – Centralised Case**

Substitution rules are applied to determine whether one type of plant can be substituted for another and a constraint is placed on the number of plants that can be built in any given year to ensure that pent up demand cannot necessarily be fulfilled the moment a particular plant type becomes viable. Figures 5.23 to 5.26 provide the reconstructed supply curves for two of the scenarios, the SUS and BAU cases, in the centralised and decentralised regimes described previously.

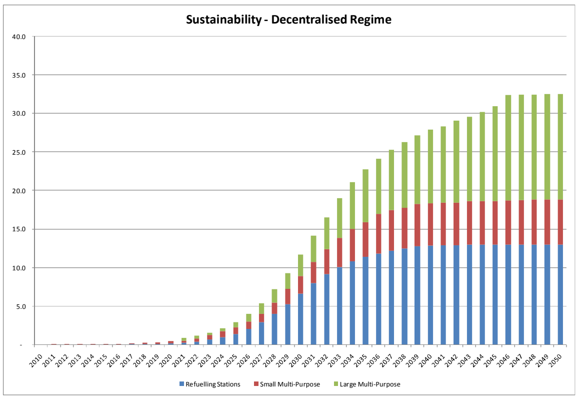



**Figure 5.23 Model Calculated Supply Curve, Decentralised Regime, SUS**

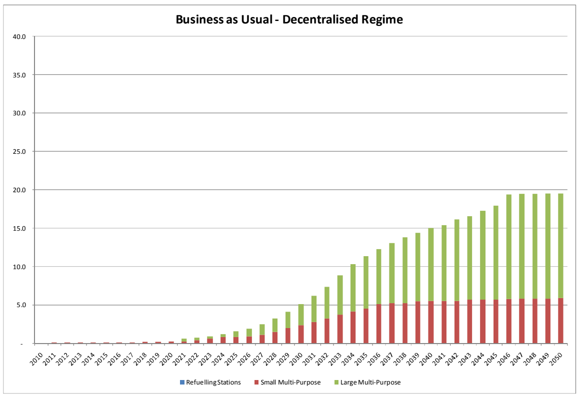



**Figure 5.24 Model Calculated Supply Curve, Decentralised Regime, BAU**

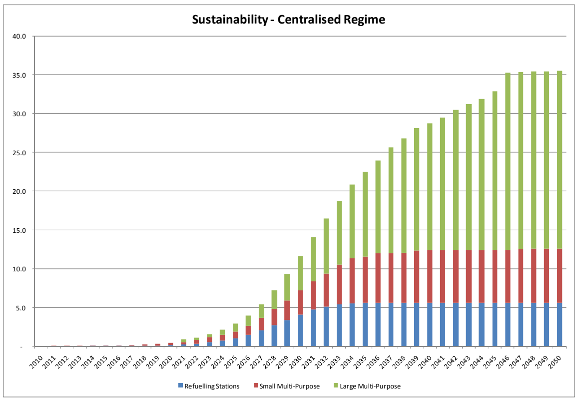



**Figure 5.25 Model Calculated Supply Curve, Centralised Regime, SUS**

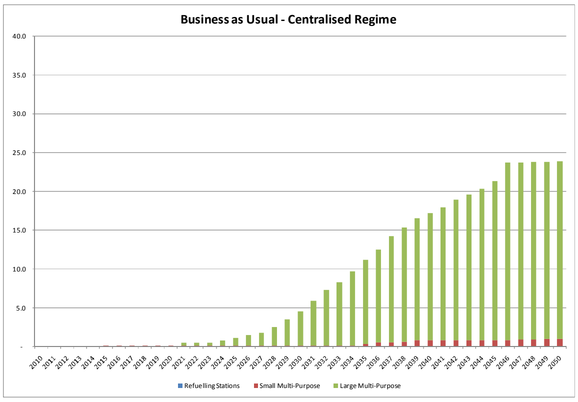



**Figure 5.26 Model Calculated Supply Curve, Centralised Regime, BAU**

Based on the substitution rules applied in the program, the analysis indicates that in the SUS scenarios the full demand would likely be met with a similar set of plant to that anticipated by the initial scenario programmed into the model. In the BAU case on the other hand, the initial anticipated demand is not met since plant types show viability only in later years (and in some cases not at all) and consequently the build up of plant is delayed relative to the SUS case. Furthermore, the type of supply infrastructure changes reflecting the relative merits of different plant types. The actual roll-out of plant in both the "centralised" and "decentralised" regimes initially envisaged places emphasis on the centralised plant which according to the model shows better economics than the decentralised plant in spite of the initial hypothesis which saw decentralised plant being favoured.

## 5.4 Chapter Summary

The first part of the analysis presented in this Chapter highlights the benefits to be gained by considering each of the three value measures together since each offers a different perspective on potential market development. As was discussed in Section 5.1, while the NPV analysis can be made standalone, the other valuation metrics based around EPS and multiples only make sense when considered in relation to specific companies. It is evident from Figures 5.1 to 5.8 that there is considerably more variability across companies when considering the EPS and multiples analysis than when considering the NPV analysis. This is reflective, on the one hand, of the significant variability in size and current EPS between the companies being considered and, on the other, the relatively similar WACC between companies. It is important to note that while the WACC varies relatively little between the companies being considered, the discount rate that they each may choose to apply to the particular projects will probably vary according to their own perception of risk (see Section 3.4). This has important implications for policy makers when considering levels of support for different technologies since the impact will vary considerably across different companies. Should levels of support be set so as to encourage those companies for which the value impact will be greatest, least, between the two or at somewhere outside the range to provide a more demanding incentive? The author's model allows these questions to be explored directly with a range of different companies through the analysis of specific projects to use these technologies. These differences from and benefits compared with cost-optimisation models would seem to justify its use as a complementary or alternative approach.

As was discussed in Section 2.5.7, the production of hydrogen transport fuel as an alternative to electricity might be a worthwhile value proposition for an electricity utility, potentially allowing scope to exploit arbitrage opportunities. In Section 5.2, an example renewables plant, with or without an attached hydrogen plant is valued and compared. While not designed to present a complete and generalised analysis of the effects of combining investments in hydrogen and electricity, this example provides data regarding the conditions under which the electricity plus hydrogen option would add value. In certain instances it can be seen that the addition of hydrogen energy production can offer higher value than a straight generation project (Figure 5.14). What this analysis suggests is that in circumstances where the price differential between electricity and transport fuel was greater than 2 times, then the electricity plus hydrogen option delivers higher NPV (see Figure 5.15). Figure 5.16 indicates that compared with the developer company's current performance, the electricity plus hydrogen case would only be earnings positive in the very upper ends of the price range considered for petrol (>18 pence per kWh), whereas the electricity option is earnings positive from roughly the base case upwards. Similarly, Figure 5.17 shows that only multiples in the very upper end of the range would allow the hydrogen plus electricity project to deliver an increase in the value of the developer on a sum-of-the-parts basis. It is worth noting that while reference is made to the upper ends of the range, the full range of values explored in this example sit within the range of observed values during the research period.

When the model is used to develop a forecast of future market development based around the demand model set out in Section 3.6.1, the analysis indicates that in the SUS scenarios the full demand would likely be met with a similar set of plant to that anticipated by the initial scenario programmed into the model (see Figures 5.23 to 5.25). In the BAU case on the other hand, the initial anticipated demand is not met since plant types show viability only in later years (and in some cases not at all) and consequently the build up of plant is delayed relative to the SUS case (Figures 5.24 and 5.26).

Furthermore, the type of supply infrastructure changes reflecting the relative merits of different plant types. The actual roll-out of plant in both the "centralised" and "decentralised" regimes initially envisaged places emphasis on the centralised plant which according to the model shows better economics than the decentralised plant in spite of the initial hypothesis.

In summary, this Chapter put together the model with the observations described below.

- The results of the company-specific analysis were presented with a commentary on the relative attractiveness of the various projects to the companies considered. The results showed that while there was a fair degree of consistency with respect to the NPV analysis there was more variability as far as the other measures concerned. This is attributable to the performance of the projects relative to the core business of these companies and also the relative size of the companies in question.

- The effects of investing in a combined electricity and hydrogen project were examined to understand the possible in order to examine the possible benefits from being able to exploit arbitrage opportunities. This was carried out with reference to a specific project, namely a large scale wind to electricity or hydrogen project in the Shetland Islands. This highlighted the fact that under certain conditions a renewable hydrogen project could offer a greater NPV than a pure renewables project. The question of relative price movements of different fuels was discussed in the context of the renewables and renewables plus hydrogen project and it was seen that arbitrage opportunities might exist. It was discussed that this could be modelled as a lower discount rate for the renewables plus hydrogen project

- Finally, the results of the capacity build-up calculations under the four different scenarios and in two different capacity type assumptions was presented. It was seen that in the BAU cases the total predicted demand would not be met since the attractiveness of the potential projects was insufficient whereas in the SUS cases plant was built out much as predicted. In the decentralised case the actual outcome was in fact centralised owing to the fact that the large plant were found to be positive contributors to value while the smaller ones were not.

# 6 Conclusions and Directions for Future Research

The final Chapter of the Thesis draws together some overall conclusions with respect to the hydrogen energy market and the application of the author's model to understand possible future developments. In addition, it provides some thoughts on future directions for research.

Before describing these conclusions and areas for further research, it is worth considering what the strengths and limitations of the approach taken by the author. As has been described in Section 1.5, the author set out to discover whether a suitable methodology for an investment-led model could be developed and applied to a particular set of data. This thesis provides ample evidence that such a model can be developed and has utility in exploring certain aspects of market development, especially the possible combinatory effects of different policy measures being applied to currently separate, yet converging, energy streams. However, the model has significant limitations in its current form which are discussed in more detail below and while the author believes that certain of these are tractable, others are not. In particular, and in common with many bottom-up techno-centric models, the model requires significant amounts of input data which must be projected far into the future. In consequence, the extent to which the results can be relied upon as a "realistic" future scenario is debatable. More importantly perhaps given the thrust of the approach, the focus on the performance of public companies in making assessments of possible future market development may be misleading. A significant amount of investment capital has flowed into the hydrogen and fuel cells sector both from the private equity community and from "behind the factory gate", i.e. internally by corporate entities. Unfortunately, data on the amount of investment and, significantly, the valuations placed upon those investments is scant leading to an almost unavoidable reliance on the valuations of public companies in the analysis. Indeed, this may not be an unreasonable assumption since professional investors will tend to take their cues from the performance of related companies in the quoted sector when making investment decisions.

## 6.1 Conclusions

It is clear from the discussions in this Thesis that the UK faces a number of serious challenges as it attempts to manage its energy infrastructure. As was demonstrated in Section 2.1), the near "perfect storm" created by a high reliance on potentially insecure sources of fossil fuels, declining production of oil and gas from the UK Continental Shelf and the demands implied by emissions reduction have created an unusually turbulent environment. The analysis presented in Chapter 3 confirmed Scotland's reliance on fossil fuels but highlighted some key differences with the UK as a whole. In particular, Scotland is currently an exporter of electricity and has lower emissions from electricity production owing to a significantly greater exploitation of its potential renewable resource (see Figures 2.3 and 3.15).

At the same time, it is clear that energy is an important contributor to UK GDP (see Section 2.2) and opportunities present themselves to create wealth through the development of new technologies and services in the energy field. One such opportunity lies in the development of hydrogen energy technologies which, it has been argued in Section 2.5, have the potential to replace the use of fossil fuels in certain applications, increasing supply security and reducing carbon emissions simultaneously. The UK possesses many skills pertinent to the development of hydrogen and fuel cells technologies (see, for example, Table 2.10) and Scotland's exceptional renewable resource provides it with a potentially attractive position with respect to producing renewable hydrogen. A potentially significant "surplus" of electricity exists which could be directed to the production of hydrogen as the Hyfutures report [103] has highlighted. Nevertheless, despite the potential benefits that hydrogen energy could represent, there are significant barriers to its implementation (see Table 2.7), even if its added-value could be demonstrated through the type of modelling proposed by the author. Hydrogen requires significant input energy to produce, which runs contrary to the clear benefits to be gained through its use in fuel cells which are more efficient than thermal-mechanical systems. It is difficult to store and tranship and for certain proposed applications these technical challenges may result in alternative systems being favoured. So, the question is, would there be appetite to invest in hydrogen production infrastructure and how can this be analysed?

It has been argued that attempts to value the benefits of implementing hydrogen and other low carbon technologies have been hampered by the modelling techniques being used. As is discussed in some detail in the literature review presented in Chapter 2, the principal methods being employed to analyse potential future developments in the energy markets, including hydrogen, are based around cost–optimisation techniques reflecting the planned approach to energy that prevailed in the past. However, it has been argued in Sections 3.1 and 3.2 that such techniques do not allow the value contribution of these energy activities to be assessed and in any case are not reflective of the investment drivers of different energy technologies. The author has argued in Section 2.6.3 that these techniques are better suited to a planned or centralised energy environment and has indeed highlighted that this was their primary purpose. The author has gone on to argue that in order to better assess both the likelihood of private companies investing in these technologies and to better understand the potential benefit to the economy of doing so, alternative models are required. A more recent body of literature, especially the work of Awerbuch [34], Botterud [1] and Gross [76] presented in Section 2.6.3, confirms this view and underpins the development of author's model. Given that the model considers market development from the perspective of the sector companies, each of which is driven by the desire to maximise shareholder value, it considers not only the basic underlying costs of the systems but also the possible revenue streams and, critically, the relative riskiness of one set of investments versus another. This last factor is particularly important as the author has discussed in Section 2.5.7, making reference to Awerbuch's oil substitution model, a variation of which is presented in Figure 2.15. Commodity fossil fuels have proven to demonstrate highly volatile prices and, it is argued, if renewably produced hydrogen can be used to reduce the effects of price volatility in the energy markets then the benefits go beyond those of increased supply security and emissions reduction.

The author's approach aims to encapsulate both a model of hydrogen plant in "project capsules" (as discussed in Section 3.6.3) but also data from the market about how investments in these might be valued (see Section 3.6.4.2) and information about individual companies (Section 3.6.4). In consequence it incorporates much of the same data as the cost optimisation models would employ but applies it in a rather different way and also takes into account what the wide body of investors believe regarding the sector's prospects and performance. In this way it is designed to mimic the investment behaviour of companies looking to make hydrogen and fuel cell investments.

The author has, therefore, performed some initial analysis of the relative performance and valuation metrics of companies across the energy sector including the hydrogen and fuel cells market (see Figures 7.1 to 7.6). While oil and gas companies have performed quite well in terms of share price performance over the period November 2006 to October 2009, those in the all other sectors have suffered and those in the $H_2$FC domain have suffered most of all. Considering valuation metrics, companies in the $H_2$FC market have shown compressing EV / R ratios, so much so that they barely enjoy a premium today over oil and gas companies despite being, in principle, at a higher growth stage of their business cycle (see Table 3.21). What this serves to highlight is that even in the case where the costs of hydrogen production could become more competitive, if investor sentiment towards the sector is weak, it is unlikely that investment will flow towards it. Herein lies the problem for hydrogen and fuel cells companies since while these companies would be expected to register growth and, ultimately improving margins, growth has stagnated and margins have if anything worsened over the period of the research (see Table 3.22). It is important to note at the point that while sector retrenchment might be apparent in the public markets, considerable investment continues to flow into hydrogen and fuel cells behind the factory gate. It has been estimated that while investment by quoted companies runs to a few hundred million dollars annually in recent years, the corresponding figure for corporate investment might be nearer to ten billion dollars. This raises the issue of whether a focus on the performance of public companies provides an adequate picture of sector investment and the answer appears to be a resounding "no". However, the lack of transparency in the private investment market makes analysis of total investment challenging and the author was unable to obtain reliable information on this "hidden" investment.

While it is not possible to directly compare the outputs of the author's model and those of a cost-optimising model, since this would require knowledge of all the input variables being employed in other models. However, through the performance of repeated runs of the model, sensitivity and scenario analysis, it is possible to compare the results directionally. The following conclusions have been drawn with regards to the development of the market:

1. The outputs described in Section 4.2 suggest that hydrogen plant could be NPV positive (and hence be developed) sooner than the cost analyses presented, for example, in the UK Strategic Framework for Hydrogen. Needless to say, there are important considerations on the demand side which have not been fully looked at here and which might well influence the results (see comments in Section 6.2). However, the initial results are surprisingly positive. Consequently, extending the model to encompass the demand and well as supply side is an important direction for future research as will be discussed in Section 6.2.

2. While in (1) the absolute performance of hydrogen plant is referred to, as discussed in Section 4.4, it is likely that it is the relative performance of investments that will be of more importance. Figures 4.87 and 4.98 demonstrate that despite the positive NPV apparent for certain hydrogen plant, these are nevertheless generally lower than for electricity plant in the base case (or, indeed, probability weighted cases, as presented in Section 4.2.2). However, there are pricing conditions where the hydrogen plant are competitive with electricity plant in terms of NPV, EPS contribution or sum-of-the-parts contribution as discussed in more detail in Section 5.1.

3. The sensitivity analysis presented in Sections 4.2.1 and 4.3.2 point to discrepancies in the levels of support being provided to electricity infrastructure

and hydrogen transport fuel infrastructure. Although hydrogen is not currently a qualifying fuel under the RTFO, the benefit has nevertheless been applied in the model. However, the effect is minimal and deeply subordinated to the changes in price. Conversely, the level of support afforded to marine energy in Scotland appears to be very high resulting in very high NPVs for wave and tidal plant early on in the analysis and diminishing over time. This has clear implications for policy makers as discussed in point (4).

4. The examination of the relative effects of different policy measures in the electricity and transport fuel markets on the value of different investments presented in Section 4.4 demonstrate the utility of the author's model in identifying and assessing counter incentives within these potentially converging markets.

5. It was shown in Section 5.1 that the propensity to invest in hydrogen plant will differ according to the characteristics of the company looking to make the investment, which again has implications for policy-makers. Since investment decision will partly be influenced by certain endogenous factors concerning the company's own financial characteristics, this presents a dilemma regarding the level of support, in contrast to the situation viewed from a purely cost perspective. There is, therefore, merit in looking at specific companies and different measures as results not consistent.

6. The potential that hydrogen energy offers a utility company to add value to an investment in electricity generation infrastructure has been explored in Section 5.2 and it has been demonstrated that under certain conditions it may indeed be more valuable to develop such a combined investment. This, once again, contrasts with the systems based approach which would tend to consider each technology individually and in comparison with competing technologies.

One further important aspect that was discussed in Section 3.7 is the question of model validation. Like any other forward looking model, validation is challenging especially when such long time frames are being considered. Historical validation is often inappropriate or unfeasible especially where no historical data exists on which to test the model and no analogous industry exists as is the case with the author's model. For this reason the model has been validated principally on the basis of a verification of the underlying theory and of the model's internal workings. However, by making reference to the market perspective on the relative performance of the various energy sectors the model tries to draw in some aggregate data on the perspective of investors which provides a useful adjunct to the bottom-up techno-economic building blocks of the model.

While the foregoing results give weight to the view that it is worthwhile to take this value-maximising approach, the model nevertheless has certain drawbacks, in its current form. Principal among these perhaps is the large number of input assumptions that the model requires, a criticism that has also been levelled at models such as MARKAL. There is no escaping the fact that the model requires a lot of inputs and, by definition, it is reliant on obtaining the best possible data on the technical and economic aspects of hydrogen systems. Related to this are the problems associated with projecting so far into the future given the increasingly speculative nature of these distant future projections. The author has endeavoured to address this by considering a broad range of scenarios and sensitivity analyses but the fact remains that any such forecast is necessarily highly uncertain. This is true of all models having such long-range time horizons and it might be more prudent to consider the outputs of the model to be "what-ifs" rather truly a forecast as was discussed in Section 2.6.3. Another issue is the incomplete modelling of company behaviour and especially the competitive interaction between them inherent in the current iteration of the model. This latter aspect is the potential subject of further research as discussed in Section 6.2.

## *6.2 Directions for Future Research*

In Section of this thesis a number of simplifications and constraints inherent within the model were outlined and briefly discussed and certain weaknesses of the model have been outlined throughout the text. While the author considers the simplifications to be reasonable for a first iteration of the model, the initial direction for future research would involve seeking to relax the constraints and to address a number of the weaknesses highlighted. This would help to ensure that the model was more representative of investment behaviour and to increase the ability of the model to accurately reflect the impact of changes to policy or the market environment. In particular, the author would seek to make changes in the following areas:

- Relax the constraints on potential future applications for hydrogen and fuel cells which have so far been relatively restricted in order to limit the complexity of the study;
- The model currently takes a rather high level approach to modelling the learning effects on capital costs and makes no attempt to address the question of economies of scale and scope. What is more, the model is currently largely silent on the question of how investment is encouraged at the early stage in order to drive down the learning curve. A more "scientific" approach to both these issues would have merit since the model is sensitive to capital cost; and
- Potentially widen the scope of companies to be considered as potential developers of hydrogen energy technology. In particular, it is considered worthwhile to explore parts of the industrial sector focusing on those companies with capabilities in the fuel cell and electrolyser fields; and
- Seek to model the demand side more completely. Currently the approach taken by the author has been to assume a certain level of demand and to test the supply response to meeting that level of demand. However, demand will be determined by the relative price elasticity of demand of different energy types and the degree to which one is truly substitutable by another. These factors are in turn influenced by the availability and take up of new or replacement applications – the availability of fuel cell vehicles, for example – and their pricing relative to existing ones. It is easy to see that such an analysis is highly complex and was considered too extensive to be incorporated into this iteration to the model.

Further future research would involve extending the model analyses to encompass all the possible energy types which are currently coded into the model but not explored by the author at this stage. These include biofuels and renewable heat as well as fossil fuel technologies and nuclear. In addition, there is a desire to start to model the demand side as well on the same value maximising basis as discussed above. Furthermore, second order effects could be explored such as the relationship between oil and electricity prices.

Moving on from these initial studies, there would be merit in increasing the robustness of the model and continuing the investigation into the investment and capital raising behaviour of the companies in the energy sector to build more empirical evidence for the relationship between the two. In addition there is work to do in terms of creating a more user-friendly interface and there might be merit in building the software within a different environment which could facilitate a wider range of possible analyses. Currently the model needs rather too much manual intervention during its operation. Finally the author would anticipate creating a decision support overlay onto the underlying program in order to facilitate the model's use by governments and companies alike.

One further adaptation of the model would be to introduce some aspects of competitive response to reflect the interaction between the companies acting in the market. Others have used multi-agent models to address this question and the author considers this to be an effective way of exploring the issues. Indeed, it is this approach that forms the basis of the author's bid to EPSRC referred to in Section 1.8.

# 7 Appendices

## 7.1 Example Macro Code

**Capacity Build Up**

```
Sub capacityBuildup()

Dim sheetCounter As Integer        ' Indexes relevant sheet
Dim caseFlag As String            ' Flags which scenario is being considered
Dim caseIndex As Integer           ' Indexes according to caseFlag

sheetCounter = 10                 ' Set counter to 10 (index number of first "Modules" sheet)

Do While sheetCounter <= 11        ' Repeat for all desired "Modules" sheets

   defineSUS sheetCounter, caseFlag, caseIndex     ' Call defineSUS Function which sets all input
parameters for SUS scenario
   newNPV caseFlag, caseIndex, sheetCounter       ' Call main calculation sub-routine

   defineSMA sheetCounter, caseFlag, caseIndex     ' Call defineSUS Function which sets all input
parameters for SMA scenario
   newNPV caseFlag, caseIndex, sheetCounter       ' Call main calculation sub-routine

   defineWMA sheetCounter, caseFlag, caseIndex     ' Call defineSUS Function which sets all input
parameters for WMA scenario
   newNPV caseFlag, caseIndex, sheetCounter       ' Call main calculation sub-routine

   defineBAU sheetCounter, caseFlag, caseIndex     ' Call defineSUS Function which sets all input
parameters for BAU scenario
   newNPV caseFlag, caseIndex, sheetCounter       ' Call main calculation sub-routine

   sheetCounter = sheetCounter + 1               ' Move to next sheet

Loop

' Reset all input parameters

Sheets("Price Scenarios").Select
   Range("C38").Select          ' Electricity price
   Selection.Value = 2.5

   Range("C66").Select          ' NG price
   Selection.Value = 1.5

   Range("C83").Select          ' Petrol price
   Selection.Value = 100

Sheets("Policy Data").Select
   Range("B4").Select          ' Carbon price
   Selection.Value = 12

   Range("B9").Select          ' ROC price
   Selection.Value = 35

   Range("B17").Select          ' Petrol duty price
   Selection.Value = 54

   Range("B21").Select          ' Low carbon fuel duty saving + RTFOC price
   Selection.Value = 35
```

```
Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = 0                'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = 0                'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning rate

End Sub

Function defineSUS(sheetCounter, caseFlag, caseIndex)

' Defines input parameters for SUS scenario

Sheets("Price Scenarios").Select
    Range("C38").Select            ' Electricity price
    Selection.Value = 2.5

    Range("C66").Select            ' NG price
    Selection.Value = 3.5

    Range("C83").Select            ' Petrol price
    Selection.Value = 180

Sheets("Policy Data").Select
    Range("B4").Select             ' Carbon price
    Selection.Value = 20

    Range("B9").Select             ' ROC price
    Selection.Value = 60

    Range("B17").Select            ' Petrol duty price
    Selection.Value = 65

    Range("B21").Select            ' Low carbon fuel duty saving + RTFOC price
    Selection.Value = 55

Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = -0.2               'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0.5    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = -0.2               'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0.5    'Learning rate

If sheetCounter = 10 Then caseFlag = "SUS Hydrogen" _
    Else caseFlag = "SUS Electricity"                'Set caseFlag to "SUS Hydrogen" or "SUS
Electricity" as appropriate

caseIndex = 0                                  ' Set caseIndex to 0; this allows indexing on results sheet

End Function
```

```
Function defineSMA(sheetCounter, caseFlag, caseIndex)

' Defines input parameters for SMA scenario; other comments as above

Sheets("Price Scenarios").Select
    Range("C38").Select          ' Electricity price
    Selection.Value = 2.5

    Range("C66").Select          ' NG price
    Selection.Value = 3.5

    Range("C83").Select          ' Petrol price
    Selection.Value = 180

Sheets("Policy Data").Select
    Range("B4").Select           ' Carbon price
    Selection.Value = 20

    Range("B9").Select           ' ROC price
    Selection.Value = 35

    Range("B17").Select          ' Petrol duty price
    Selection.Value = 54

    Range("B21").Select          ' Low carbon fuel duty saving + RTFOC price
    Selection.Value = 35

Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = -0.1              'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = -0.1              'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning rate

If sheetCounter = 10 Then caseFlag = "SUS Hydrogen" _
    Else caseFlag = "SUS Electricity"             'Set caseFlag to "SUS Hydrogen" or "SUS
Electricity" as appropriate

If sheetCounter = 10 Then caseFlag = "SMA Hydrogen" Else caseFlag = "SMA Electricity"
caseIndex = 4                    'Set caseIndex to 7

End Function

Function defineWMA(sheetCounter, caseFlag, caseIndex)

' Defines input parameters for WMA scenario; other comments as above

Sheets("Price Scenarios").Select
    Range("C38").Select          ' Electricity price
    Selection.Value = 4.5

    Range("C66").Select          ' NG price
    Selection.Value = 1

    Range("C83").Select          ' Petrol price
```

```
   Selection.Value = 90

Sheets("Policy Data").Select
   Range("B4").Select             ' Carbon price
   Selection.Value = 20

   Range("B9").Select             ' ROC price
   Selection.Value = 60

   Range("B17").Select            ' Petrol duty price
   Selection.Value = 65

   Range("B21").Select            ' Low carbon fuel duty saving + RTFOC price
   Selection.Value = 55

Sheets("Hydrogen Modules").Select
   Range("J3").Select
   Selection.Value = -0.15              'Hydrogen investment adjustment factor
   Selection.Offset(0, 1).Value = 0.5    'Learning Rate

Sheets("Electricity Modules").Select
   Range("J3").Select
   Selection.Value = -0.15              'Renewables investment adjustment factor
   Selection.Offset(0, 1).Value = 0.5    'Learning rate

If sheetCounter = 10 Then caseFlag = "SUS Hydrogen" _
   Else caseFlag = "SUS Electricity"                'Set caseFlag to "SUS Hydrogen" or "SUS
Electricity" as appropriate

If sheetCounter = 10 Then caseFlag = "WMA Hydrogen" Else caseFlag = "WMA Electricity"
caseIndex = 8                      'Set caseIndex to 14

End Function

Function defineBAU(sheetCounter, caseFlag, caseIndex)

' Defines input parameters for BAU scenario; other comments as above

Sheets("Price Scenarios").Select
   Range("C38").Select            ' Electricity price
   Selection.Value = 4.5

   Range("C66").Select            ' NG price
   Selection.Value = 1

   Range("C83").Select            ' Petrol price
   Selection.Value = 90

Sheets("Policy Data").Select
   Range("B4").Select             ' Carbon price
   Selection.Value = 12

   Range("B9").Select             ' ROC price
   Selection.Value = 35

   Range("B17").Select            ' Petrol duty price
   Selection.Value = 54
```

```
   Range("B21").Select            ' Low carbon fuel duty saving + RTFOC price
   Selection.Value = 35

Sheets("Hydrogen Modules").Select
   Range("J3").Select
   Selection.Value = 0.05              'Hydrogen investment adjustment factor
   Selection.Offset(0, 1).Value = -0.5    'Learning Rate

Sheets("Electricity Modules").Select
   Range("J3").Select
   Selection.Value = 0.05              'Renewables investment adjustment factor
   Selection.Offset(0, 1).Value = -0.5    'Learning rate

If sheetCounter = 10 Then caseFlag = "SUS Hydrogen" _
   Else caseFlag = "SUS Electricity"               'Set caseFlag to "SUS Hydrogen" or "SUS
Electricity" as appropriate

If sheetCounter = 10 Then caseFlag = "BAU Hydrogen" Else caseFlag = "BAU Electricity"
caseIndex = 12                       'Set caseIndex to 21

End Function

Sub newNPV(caseFlag, caseIndex, sheetCounter)

' Set up vaiables

Dim industryCategory As String            'Industry the company or activity is in
Dim debtProportion(10 To 15) As Single      'Fraction of investment funded by debt
Dim period As Integer                    'Year relating to given NPV calculation
Dim discountRate(41) As Single            'Discount rate to be applied in a given NPV year
Dim category As String                   'Plant variant
Dim lifetime As Integer                  'Lifetime of given plant variant
Dim yearCounter As Integer                 'Counts the cashflow periods for a given NPV calculation
Dim cumulativeCF As Single                 'Holds the cumulative present value of cashflows for a given
NPV calc.
Dim startYear As Integer                  'Initial year of analysis
Dim investment As Single                  'Capital investment for given project
Dim depreciation As Single                'Chargeable depreciation figure for a given CF period
Dim tax As Single                       'Corporation tax rate for a given CF period
Dim operatingCosts As Single               'Operating costs to be applied for a given CF period
Dim depreciationPeriod As Integer           'Period over which a given project is depreciated
Dim ebitda As Single                     'Earnings before interest, tax, amortisation and depreciation for
given CF period
Dim carbonTax As Single                   'Tax to be applied to carbon emissions from project in given
CF period
Dim corporateTax As Single                 'Corporation tax to be applied to profits in given CF period
Dim counter As Integer                   'General counter
Dim currentCF As Single                   'CF in a given period
Dim cashflowPv As Single                  'Present value of a CF in a given period
Dim earnings As Single                   'Earnings in a given CF period
Dim npvCalc As Single                    'NPV for a given project and year
Dim rowCounter As Integer                  'Counts the row in the projectCapsules array
Dim projectCapsules(1 To 1500, 1 To 100) As Variant 'Array which holds all the data relating to
projects by year and CF period
Dim interest As Single                   'Annual interest payment to be applied in each cashflow period of
particular project/year
Dim count1 As Integer
Dim count2 As Integer
```

```
Dim numberVariants As Integer

If sheetCounter = 10 Then numberVariants = 13 Else numberVariants = 8

Sheets("Assumptions").Select            'Go to Assumptions sheet and capture user-inputted number of
trials
Range("C2").Select

Sheets(sheetCounter).Select                     ' Select sheet
findStartYear startYear                         ' Find Start Year and save to variable
findDR discountRate                             ' Fill discount rate array
Range("B1").Select                              ' Go to top of category column
debtProportion(sheetCounter) = Selection.Offset(2, 2)   'Capture proportion of debt used in financing

    rowCounter = 1                      ' Set rowCounter to 1

    Application.Calculate               ' Update entire workbook

    Range("B1").Select                  ' Go to top of category column

    Do Until Selection.Value = "EndData"   ' Repeat for all categories of module (plant variants)

        categorySelect category, lifetime, depreciationPeriod, industryCategory ' Go to sub-routine to
select plant variant
        findInputCell
        period = startYear              ' Set year to be startYear

        Do Until period = 2050 + 1          ' Calculate NPV for all years up to 2050

            findTax corporateTax, startYear, period     ' Capture tax rate for the year
            Sheets(sheetCounter).Select                 ' Select sheet
            projectCapsules(rowCounter, 1) = category   ' Insert module category into appropriate row and
first column
            projectCapsules(rowCounter, 2) = period     ' Insert year into appropriate row, second column
            projectCapsules(rowCounter, 3) = industryCategory  ' Insert plant variant into appropriate row,
third column
            projectCapsules(rowCounter, 4) = lifetime   ' Insert lifetime into appropriate row, 4th column
            cumulativeCF = 0                            ' Reset CumulativeCF
            yearCounter = 1                             ' Reset yearCounter
            interest = Selection.Offset(-5, 0)          ' Capture interest for project begun in that year
            investment = Selection.Offset(-1, 0)        ' Capture investment for project begun in that year

            'Call PV calculation sub-routine

            cashflowCalc rowCounter, projectCapsules, cumulativeCF, yearCounter, interest, investment,
_
                depreciation, corporateTax, depreciationPeriod, discountRate, lifetime, countTrials

            projectCapsules(rowCounter, 6) = -investment    ' Captures investment into array
            npvCalc = cumulativeCF - investment             ' Calculate NPV
            projectCapsules(rowCounter, 5) = npvCalc        ' Captures NPV into array
            Selection.Value = npvCalc                       ' Inserts NPV in spreadsheet
            period = period + 1                             ' Moves on to calculate next NPV
            Selection.Offset(0, 1).Select                   ' Moves cursor one cell to right
            rowCounter = rowCounter + 1                     ' Move to next row

        Loop
```

```
        Selection.Offset(1, -63).Select         ' Shift back to Category column
        rowCounter = rowCounter + 1             ' Move to next row

    Loop

projectCapsules(rowCounter, 1) = endData        ' Inserts the word endData into array
'companyValue projectCapsules, startYear, debtProportion, lifetime, caseFlag, caseIndex,
sheetCounter ' Calls companyValue sub-routine

displayResults sheetCounter, caseIndex, count1, count2, projectCapsules, numberVariants

End Sub

Function findStartYear(startYear)

'Finds first year to be considered

    Range("v1").Select                  'Move cursor to top of P&L headings column
    Do Until Selection.Value = "Year"   'Move cursor down until row with the word "Year"
        Selection.Offset(1, 0).Select
    Loop
    Selection.Offset(0, 1).Select       'Move cursor to right
    startYear = Selection.Value         'Fill startYear variable

End Function

Function findDR(discountRate)

'Finds appropriate discount rate

Dim int1 As Integer     'Set counter variable

For int1 = 0 To 41      'Repeat for each project year
    discountRate(int1) = Selection.Offset(3, 0).Value   'Capture discount rate for given year
    Selection.Offset(0, 1).Select                       'Move cursor one cell to right

Next

End Function

Sub categorySelect(category, lifetime, depreciationPeriod, industryCategory)

' Finds plant variant as well as Lifetime, Depreciation Period and Industry Category for that plant
variant

    Do Until Selection.Value <> ""                  ' Find first category by moving cursor down until non-
null cell reached
        Selection.Offset(1, 0).Select
    Loop

    category = Selection.Value                          ' Set category
    industryCategory = Selection.Offset(0, 2).Value     ' Set industry category
    lifetime = Selection.Offset(0, 18).Value            ' Set lifetime
    depreciationPeriod = Selection.Offset(0, 19).Value  ' Set Depreciation Period

End Sub

Function findInputCell()
```

```
'Moves cursor to correct first input cell

    Selection.Offset(0, 20).Select          ' Move to the P&L headings column
    Do Until Selection.Value = "Basic NPV"  ' Move cursor down until NPV row reached
        Selection.Offset(1, 0).Select
    Loop
    Selection.Offset(0, 1).Select           ' Move cursor one cell to right

End Function

Function findTax(corporateTax, startYear, period)

'Finds and loads corporate tax rate data

    Sheets("Assumptions").Select                    ' Go to Assumptions sheet
    If period = startYear Then Range("C19").Select _
    Else Selection.Offset(0, 1).Select              ' If first year go to target cell otherwise shift from
previous cell
    corporateTax = Selection.Value                  ' Capture value

End Function

Sub cashflowCalc(rowCounter, projectCapsules, cumulativeCF, yearCounter, interest, investment, _
        depreciation, corporateTax, depreciationPeriod, discountRate, lifetime, countTrials)

' Calculation of present value of future cashflows

Dim revenues As Single                          ' Define the Revenue variable

Do Until yearCounter = lifetime + 1                 ' Repeat for each year of the project lifetime

    revenues = Selection.Offset(-13, yearCounter - 1)   ' Capture revenues for given year
    ebitda = Selection.Offset(-7, yearCounter - 1)      ' Capture ebitda for given year
    carbonTax = Selection.Offset(-3, yearCounter - 1)   ' Capture carbon tax

    ' Capture depreciation which will be zero once fully depreciated

    If yearCounter <= depreciationPeriod Then _
        depreciation = Selection.Offset(-6, 0) _
        Else depreciation = 0

    ' Calculate tax based on pretax profit (zero if pretax is zero)

    If (ebitda - depreciation - interest) <= 0 Then _
        tax = 0 _
        Else tax = (ebitda - depreciation - interest) * corporateTax

    projectCapsules(rowCounter, yearCounter + 37) = revenues    ' Store revenues in the
projectCapsules array

    projectCapsules(rowCounter, yearCounter + 68) = _
        ebitda - depreciation - interest - tax - carbonTax      ' Store earnings in projectCapsules Array

    projectCapsules(rowCounter, yearCounter + 6) = ebitda - tax - carbonTax ' Store CF in
projectCapsules Array

    cashflowPv = (ebitda - tax - carbonTax) / _
```

```
    (1 + discountRate(yearCounter)) ^ yearCounter   ' Calculate PV of Cash Flow

  cumulativeCF = cumulativeCF + cashflowPv          ' Calculate Cumulative PV Cash Flow

  yearCounter = yearCounter + 1                     ' Move to next period

Loop

End Sub

Sub companyValue(projectCapsules, startYear, debtProportion, lifetime, caseFlag, caseIndex,
sheetCounter)

'Calculates the potential value impact of each project on a set of companies of the projects

Dim companyRegister(30, 15) As Variant         'Contains details of selected companies
Dim categoryHeadings As Integer             'Counter for informatin categories
Dim companyHeadings As Integer               'Counter of number of companies
Dim companyName As String                   'Name of Company
Dim percentDilution As Single               'Define variable that will hold accretion / dilution in year
10 of given project
Dim sectorMultiples(1 To 5, 1 To 2) As Variant  'Industry sector name and associated revenue and
profit multiple
Dim impliedPrice As Single                  'Implied share price of given company
Dim newShares As Single                     'Number of new shares issued to finance project
Dim count1 As Integer                       'Counts through all plant variants
Dim count2 As Integer                       'Counts through the three year cases
Dim caseLine As Integer                      'Indexes correct row in projectCapsules array
Dim numberVariants As Integer                'Number of plant variants

If sheetCounter = 10 Then numberVariants = 13 Else numberVariants = 12  'Defines number of plant
variants to be displayed

coreData companyRegister, sectorMultiples      'Calls Function which accesses core company data

For companyHeadings = 1 To 13                       'Repeat for all companies

  companyName = companyRegister(0, companyHeadings)   'Load name of company into
companyName
  Sheets(companyName).Select                      'Go to sheet referring to that company

  If caseFlag = "SUS Hydrogen" Then               'Only output company data if first cycle (since data
stays the same during run)

    Range("A3").Select                'Move cursor to cell A3

    For categoryHeadings = 0 To 27      'Repeat for all categories of data

      Selection.Offset(categoryHeadings, 0).Value = companyRegister(categoryHeadings, 0)
'Insert headings into sheet
      Selection.Offset(categoryHeadings, 1).Value = companyRegister(categoryHeadings,
companyHeadings)   'Insert data into sheet

    Next

  End If

  Range("A31").Select     'Move cursor to cell A31, i.e. above main data output section
```

```
   Do Until Selection.Value = caseFlag ' Index to line corresponding to scenario being calculated

      Selection.Offset(1, 0).Select

   Loop

   Selection.Offset(0, 3).Select          ' Move cursor to first output cell

   For count1 = 1 To numberVariants       ' Repeat for all plant variants

      For count2 = 2015 To 2035 Step 10   ' Repeat for years 2015, 2025 and 2035

         caseLine = (count2 - 2015 + 7) + (count1 - 1) * 43             ' Identify appropriate "line"
location in array

         calculateNPV projectCapsules, companyRegister, caseLine, _
            companyHeadings, cumulativeCF                                   ' Call calculateNPV function
         Selection.Value = cumulativeCF + projectCapsules(caseLine, 6)             ' Outputs NPV for
the given year

         calculateDilution lifetime, percentDilution, projectCapsules, caseLine, _
            debtProportion, companyRegister, companyHeadings, newShares            ' Call
calculateDilution Function

         Selection.Offset(0, 4).Value = percentDilution                          ' Outputs dilution for given
year

         calculateRevenuemultiple lifetime, impliedPrice, projectCapsules, caseLine, _
            sectorMultiples, newShares, companyRegister, companyHeadings       ' Call
calculateRevenuemultiple Function
         Selection.Offset(0, 8).Value = impliedPrice                          ' Output revenue multiple
calculation for given year

         calculateEarningsmultiple impliedPrice, projectCapsules, caseLine, _
            sectorMultiples, newShares, companyRegister, companyHeadings       ' Call
calculateEarningsmutiple Function
         Selection.Offset(0, 12).Value = impliedPrice                        ' Output earnings multiple
calculation for given year

         Selection.Offset(0, 1).Select   ' Move down one cell

      Next

      Selection.Offset(1, -3).Select      ' Move down one cell and move back to first column

   Next


Next

End Sub

Function coreData(companyRegister, sectorMultiples)

'Gathers key data on each company and on sector multiples
```

```
categoryHeadings = 0    'Set variables to zero
companyHeadings = 0

Sheets("Sector Multiples").Select   'Go to the sheet containing sector multiples
Range("A1").Select                  'Move cursor to cell A1

sectorMultiples(1, 1) = Selection.Offset(1, 1)  'Gather sector multiple data; EV / R and P / E
sectorMultiples(1, 2) = Selection.Offset(1, 2)
sectorMultiples(2, 1) = Selection.Offset(2, 1)
sectorMultiples(2, 2) = Selection.Offset(2, 2)
sectorMultiples(3, 1) = Selection.Offset(3, 1)
sectorMultiples(3, 2) = Selection.Offset(3, 2)
sectorMultiples(4, 1) = Selection.Offset(4, 1)
sectorMultiples(4, 2) = Selection.Offset(4, 2)
sectorMultiples(5, 1) = Selection.Offset(5, 1)
sectorMultiples(5, 2) = Selection.Offset(5, 2)

Sheets("Company Data").Select       'Go to sheet containing all company core data
Range("A4").Select                  'Move cursor to cell A4

Do Until Selection.Offset(0, companyHeadings).Value = ""    'Repeat for all companies

   Do Until Selection.Offset(categoryHeadings, 0) = ""     'Repeat for all data categories

      companyRegister(categoryHeadings, companyHeadings) = Selection.Offset(categoryHeadings,
companyHeadings).Value 'Load data into array
      categoryHeadings = categoryHeadings + 1 'Move to next category

   Loop

   categoryHeadings = 0                    'Reset category heading
   companyHeadings = companyHeadings + 1       'Move to next company

Loop

End Function

Function calculateNPV(projectCapsules, companyRegister, caseLine, companyHeadings,
cumulativeCF)

'Calculates PV of future CFs

Dim discountFactor As Single       'Define discountFactor which will hold DR for particular company
Dim presentCashflow As Single       'Define presentCashflow which will hold the discounted CF

cashflowYear = 1        'Select year 1
cumulativeCF = 0        'Set cumulative CF to zero
presentCashflow = 0     'Set presentCashflow to zero

Do Until projectCapsules(caseLine, cashflowYear + 6) = "" 'Repeat for all CFs for given year

   discountFactor = (1 + companyRegister(17, companyHeadings)) ^ (cashflowYear)           'Calculate
DR based on company info
   presentCashflow = projectCapsules(caseLine, cashflowYear + 6) / discountFactor         'Calculate
PV of CF based on company DR
   cumulativeCF = cumulativeCF + presentCashflow                              'Caclulate cumulative
cashflow
   cashflowYear = cashflowYear + 1                                         'Move to next CF year
```

```
Loop

End Function

Function calculateDilution(lifetime, percentDilution, projectCapsules, caseLine, debtProportion,
companyRegister, companyHeadings, newShares)

'Calculates potential earnings dilution for each project for each company

Dim yeartenEarnings As Single   ' Define variable that will hold year 10 earnings
Dim newEarnings As Single       ' Define variable to hold earnings including additional project

lifetime = projectCapsules(caseLine, 4)   ' Pick up lifetime value



yeartenEarnings = projectCapsules(caseLine, 78)           ' Pick up year 10 earnings for given year

newShares = -projectCapsules(caseLine, 6) * (1 - debtProportion(10)) / _
   (companyRegister(18, companyHeadings) / 100)                        ' Calculate number of new shares
to be issued

newEarnings = (yeartenEarnings + companyRegister(5, companyHeadings))       ' Calculate quantum
of new earnings


yeartenDilution = newEarnings * 100 / (newShares + companyRegister(9, companyHeadings)) _
   - companyRegister(7, companyHeadings)                               ' Calculate accretion / dilution in
year 10 of project


percentDilution = yeartenDilution / companyRegister(7, companyHeadings)    ' Calculate precentage
dilution

End Function

Function calculateRevenuemultiple(lifetime, impliedPrice, projectCapsules, caseLine,
sectorMultiples, newShares, companyRegister, companyHeadings)

'Calculates value contributed based on revenue multiple

Dim revenueValue As Single  'Define variable to hold value of revenue-based value of project

Select Case projectCapsules(caseLine, 3)  'Select multiple based on project type (industry multiple)
and calculate value contribution

   Case "H2FC"
      revenueValue = projectCapsules(caseLine, 47) * sectorMultiples(1, 1)
   Case "AltUte"
      revenueValue = projectCapsules(caseLine, 47) * sectorMultiples(2, 1)
   Case "TradUte"
      revenueValue = projectCapsules(caseLine, 47) * sectorMultiples(3, 1)
   Case "BioFuels"
      revenueValue = projectCapsules(caseLine, 47) * sectorMultiples(4, 1)
   Case "OilGas"
      revenueValue = projectCapsules(caseLine, 47) * sectorMultiples(5, 1)
```

```
End Select

'Calculate implied price based on revenue multiple

impliedPrice = 100 * (companyRegister(20, companyHeadings) + revenueValue _
        - companyRegister(11, companyHeadings) + companyRegister(10, companyHeadings)) /
_
        (newShares + companyRegister(9, companyHeadings))

End Function

Function calculateEarningsmultiple(impliedPrice, projectCapsules, caseLine, sectorMultiples,
newShares, companyRegister, companyHeadings)

'Calculates valure contributed based on earnings multiple

Dim earningsValue As Single 'Define variable to hold value of earnings-based value of project

Select Case projectCapsules(caseLine, 3)  'Select multiple based on project type (industry multiple)
and calculate value contribution
  Case "H2FC"
    earningsValue = projectCapsules(caseLine, (2 * lifetime + 18)) * sectorMultiples(1, 2)
  Case "AltUte"
    earningsValue = projectCapsules(caseLine, (2 * lifetime + 18)) * sectorMultiples(2, 2)
  Case "TradUte"
    earningsValue = projectCapsules(caseLine, (2 * lifetime + 18)) * sectorMultiples(3, 2)
  Case "BioFuels"
    earningsValue = projectCapsules(caseLine, (2 * lifetime + 18)) * sectorMultiples(4, 2)
  Case "OilGas"
    earningsValue = projectCapsules(caseLine, (2 * lifetime + 18)) * sectorMultiples(5, 2)

End Select

'Calculate implied price based on revenue multiple

impliedPrice = 100 * (companyRegister(20, companyHeadings) + earningsValue _
        - companyRegister(11, companyHeadings) + companyRegister(10, companyHeadings)) /
_
        (newShares + companyRegister(9, companyHeadings))

End Function

Sub displayResults(sheetCounter, caseIndex, count1, count2, projectCapsules, numberVariants)

'Outputs statistical data to appropriate sheet



If sheetCounter = 10 Then Sheets("H2 Results").Select Else Sheets("Electricity Results").Select    'Go
to output sheet


Range("B2").Select          'Select top of years column


For count1 = 1 To numberVariants    'Repeat for all plant variants

  For count2 = 1 To 43        'Repeat for all project years
```

```
        Selection.Offset(1, 0).Select   'Move down one cell
        If count2 = 43 Then Selection.Offset(0, 1).Value = ""
        If count2 <> 43 Then
        Selection.Offset(0, 1 + caseIndex).Value = projectCapsules((count1 - 1) * 43 + count2, 5)
'Ouput NPV 1, 5, 9 or 13 cells to right depending on scenario

        Selection.Offset(0, 2 + caseIndex).Value = projectCapsules((count1 - 1) * 43 + count2, 47)
'Output Revenue 2, 6, 10 or 14 cells to right depending on scenario

        Selection.Offset(0, 3 + caseIndex).Value = projectCapsules((count1 - 1) * 43 + count2, 78)
'Output Earnings 3, 7, 11 or 15 cells to right depending on scenario

        End If

    Next

Next

End Sub
```

## Monte Carlo Macro

```
Sub montecarloModel()

Dim sheetCounter As Integer        ' Indexes relevant sheet
Dim caseFlag As Integer           ' Flags which scenario is being considered

sheetCounter = 10                 ' Set counter to 10 (index number of first "Modules" sheet)

Do While sheetCounter <= 12        ' Repeat for all "Modules" sheets


   defineSUS caseFlag            ' Call defineSUS Function which sets all input parameters for SUS
scenario
   newNPV caseFlag, sheetCounter   ' Call main calculation sub-routine

   defineSMA caseFlag            ' Call defineSUS Function which sets all input parameters for SMA
scenario
   newNPV caseFlag, sheetCounter

   defineWMA caseFlag            ' Call defineSUS Function which sets all input parameters for WMA
scenario
   newNPV caseFlag, sheetCounter

   defineBAU caseFlag            ' Call defineSUS Function which sets all input parameters for BAU
scenario
   newNPV caseFlag, sheetCounter

   sheetCounter = sheetCounter + 2 ' Move to next sheet

' Reset all input parameters

Sheets("Price Scenarios").Select
   Range("C36").Select           ' Electricity price
   Selection.Value = 2.5

   Range("C60").Select           ' NG price
   Selection.Value = 1.5

   Range("C77").Select           ' Petrol price
   Selection.Value = 100

   Range("C93").Select           ' Coal Price
   Selection.Value = 60

Sheets("Policy Data").Select
   Range("B5").Select            ' Carbon price
   Selection.Value = 12

   Range("B12").Select           ' ROC price
   Selection.Value = 35

   Range("B22").Select           ' Petrol duty price
   Selection.Value = 54

   Range("B27").Select           ' Low carbon fuel duty saving + RTFOC price
   Selection.Value = 35
```

```
Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = 0                'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = 0                'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning rate



Loop

End Sub

Function defineSUS(caseFlag)

' Defines input parameters for SUS scenario

Sheets("Price Scenarios").Select
    Range("C36").Select            ' Electricity price
    Selection.Value = 2.5

    Range("C60").Select            ' NG price
    Selection.Value = 3.5

    Range("C77").Select            ' Petrol price
    Selection.Value = 180

Sheets("Policy Data").Select
    Range("B5").Select             ' Carbon price
    Selection.Value = 20

    Range("B12").Select             ' ROC price
    Selection.Value = 60

    Range("B22").Select            ' Petrol duty price
    Selection.Value = 65

    Range("B27").Select            ' Low carbon fuel duty saving + RTFOC price
    Selection.Value = 55

    Range("C93").Select            ' Coal Price
    Selection.Value = 100

Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = -0.2               'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0.5    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = -0.2               'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0.5    'Learning rate
```

```
caseFlag = 0                    ' Set caseFlag to 0

End Function

Function defineSMA(caseFlag)

' Defines input parameters for SMA scenario; other comments as above

Sheets("Price Scenarios").Select
    Range("C36").Select
    Selection.Value = 2.5

    Range("C60").Select
    Selection.Value = 3.5

    Range("C77").Select
    Selection.Value = 180

Sheets("Policy Data").Select
    Range("B5").Select
    Selection.Value = 20

    Range("B12").Select
    Selection.Value = 35

    Range("B22").Select
    Selection.Value = 54

    Range("B27").Select
    Selection.Value = 35

    Range("C93").Select            ' Coal Price
    Selection.Value = 100

Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = -0.1              'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = -0.1              'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0    'Learning rate


caseFlag = 7                    'Set caseFlag to 7

End Function

Function defineWMA(caseFlag)

' Defines input parameters for WMA scenario; other comments as above

Sheets("Price Scenarios").Select
    Range("C36").Select
    Selection.Value = 4.5

    Range("C60").Select
```

```
    Selection.Value = 1

    Range("C77").Select
    Selection.Value = 90

Sheets("Policy Data").Select
    Range("B5").Select
    Selection.Value = 20

    Range("B12").Select
    Selection.Value = 60

    Range("B22").Select
    Selection.Value = 65

    Range("B27").Select
    Selection.Value = 55

    Range("C93").Select             ' Coal Price
    Selection.Value = 50

Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = -0.15                'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = 0.5    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = -0.15                'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = 0.5    'Learning rate


caseFlag = 14                      'Set caseFlag to 14

End Function

Function defineBAU(caseFlag)

' Defines input parameters for BAU scenario; other comments as above

Sheets("Price Scenarios").Select
    Range("C36").Select
    Selection.Value = 4.5

    Range("C60").Select
    Selection.Value = 1

    Range("C77").Select
    Selection.Value = 90

Sheets("Policy Data").Select
    Range("B5").Select
    Selection.Value = 12

    Range("B12").Select
    Selection.Value = 35

    Range("B22").Select
```

```
    Selection.Value = 54

    Range("B27").Select
    Selection.Value = 35

    Range("C93").Select            ' Coal Price
    Selection.Value = 50

Sheets("Hydrogen Modules").Select
    Range("J3").Select
    Selection.Value = 0.05              'Hydrogen investment adjustment factor
    Selection.Offset(0, 1).Value = -0.5    'Learning Rate

Sheets("Electricity Modules").Select
    Range("J3").Select
    Selection.Value = 0.05              'Renewables investment adjustment factor
    Selection.Offset(0, 1).Value = -0.5    'Learning rate


caseFlag = 21                    'Set caseFlag to 21

End Function

Sub newNPV(caseFlag, sheetCounter)

' Set up vaiables

Dim industryCategory As String            'Industry the company or activity is in
Dim debtProportion(10 To 15) As Single      'Fraction of investment funded by debt
Dim period As Integer                    'Year relating to given NPV calculation
Dim discountRate(41) As Single            'Discount rate to be applied in a given NPV year
Dim category As String                   'Plant variant
Dim lifetime As Integer                  'Lifetime of given plant variant
Dim yearCounter As Integer                'Counts the cashflow periods for a given NPV calculation
Dim cumulativeCF As Single                'Holds the cumulative present value of cashflows for a given
NPV calc.
Dim startYear As Integer                  'Initial year of analysis
Dim investment As Single                  'Capital investment for given project
Dim depreciation As Single                'Chargeable depreciation figure for a given CF period
Dim tax As Single                        'Corporation tax rate for a given CF period
Dim operatingCosts As Single              'Operating costs to be applied for a given CF period
Dim depreciationPeriod As Integer          'Period over which a given project is depreciated
Dim ebitda As Single                     'Earnings before interest, tax, amortisation and depreciation for
given CF period
Dim carbonTax As Single                   'Tax to be applied to carbon emissions from project in given
CF period
Dim corporateTax As Single                'Corporation tax to be applied to profits in given CF period
Dim counter As Integer                   'General counter
Dim currentCF As Single                  'CF in a given period
Dim cashflowPv As Single                 'Present value of a CF in a given period
Dim earnings As Single                   'Earnings in a given CF period
Dim npvCalc As Single                    'NPV for a given project and year
Dim rowCounter As Integer                 'Counts the row in the projectCapsules array
Dim projectCapsules(1 To 1500, 1 To 100, 1 To 101) As Variant 'Array which holds all the data
relating to projects by year and CF period
Dim interest As Single                   'Annual interest payment to be applied in each cashflow period of
particular project/year
Dim countTrials As Integer                'Counts number of tests carried out
```

```
Dim numberTrials As Integer             'Holds number of trials to be carried out

Sheets("Assumptions").Select            'Go to Assumptions sheet and capture user-inputted number of
trials
Range("C2").Select
numberTrials = Selection.Value

Sheets(sheetCounter).Select                     ' Select sheet
findStartYear startYear                       ' Find Start Year and save to variable
findDR discountRate                           ' Fill discount rate array
Range("B1").Select                           ' Go to top of category column
debtProportion(sheetCounter) = Selection.Offset(2, 2)   ' Capture proportion of debt used in financing

For countTrials = 1 To numberTrials                         'Repeat for chosen number of trials

   rowCounter = 1                          ' Set rowCounter to 1

   Application.Calculate

   Range("B1").Select                  ' Go to top of category column

   Do Until Selection.Value = "EndData"    ' Repeat for all categories of module

      categorySelect category, lifetime, depreciationPeriod, industryCategory              ' Go to sub-
routine to select category
      findInputCell
      period = startYear                ' Set year to be startYear

      Do Until period = 2050 + 1                   'Calculate NPV for all years up to 2050

         findTax corporateTax, startYear, period     ' Capture tax rate for the year
         Sheets(sheetCounter).Select               ' Select sheet
         projectCapsules(rowCounter, 1, countTrials) = category   ' Insert module category into
appropriate row and first column
         projectCapsules(rowCounter, 2, countTrials) = period     ' Insert year into appropriate row,
second column
         projectCapsules(rowCounter, 3, countTrials) = industryCategory  'Insert plant variant into
appropriate row, third column
         projectCapsules(rowCounter, 4, countTrials) = lifetime  'Insert lifetime into appropriate row,
4th column
         cumulativeCF = 0                        ' Reset CumulativeCF
         yearCounter = 1                         ' Reset yearCounter
         interest = Selection.Offset(-5, 0)         ' Capture interest for project begun in that year
         investment = Selection.Offset(-1, 0)        ' Capture investment for project begun in that year

         'Call PV calculation sub-routine

         cashflowCalc rowCounter, projectCapsules, cumulativeCF, yearCounter, interest, investment,
_
            depreciation, corporateTax, depreciationPeriod, discountRate, lifetime, countTrials

         projectCapsules(rowCounter, 6, countTrials) = -investment   ' Captures investment into array
         npvCalc = cumulativeCF - investment                     ' Calculate NPV
         projectCapsules(rowCounter, 5, countTrials) = npvCalc       ' Captures NPV into array
         Selection.Value = npvCalc                            ' Inserts NPV in spreadsheet
         period = period + 1                               ' Moves on to calculate next NPV
         Selection.Offset(0, 1).Select                        ' Moves cursor one cell to right
         rowCounter = rowCounter + 1                            ' Move to next row
```

```
      Loop

      Selection.Offset(1, -63).Select        ' Shift back to Category column
      rowCounter = rowCounter + 1            ' Move to next row

   Loop

Next

calculateMean projectCapsules, sheetCounter, caseFlag, numberTrials       'Calls sub-routine which
calculates the mean and SD of simulation output

projectCapsules(rowCounter, 1, countTrials) = endData       'Inserts the word endData into array

End Sub

Function findStartYear(startYear)

'Finds first year to be considered

   Range("v1").Select                 'Move cursor to top of P&L headings column
   Do Until Selection.Value = "Year"   'Move cursor down until row with the word "Year"
      Selection.Offset(1, 0).Select
   Loop
   Selection.Offset(0, 1).Select       'Move cursor to right
   startYear = Selection.Value         'Fill startYear variable

End Function

Function findDR(discountRate)

'Finds appropriate discount rate

Dim int1 As Integer     'Set counter variable

For int1 = 0 To 41      'Repeat for each project year
   discountRate(int1) = Selection.Offset(3, 0).Value   'Capture discount rate for given year
   Selection.Offset(0, 1).Select                       'Move cursor one cell to right

Next

End Function

Sub categorySelect(category, lifetime, depreciationPeriod, industryCategory)

' Finds plant variant as well as Lifetime, Depreciation Period and Industry Category for that plant
variant

   Do Until Selection.Value <> ""                    ' Find first category by moving cursor down until non-
null cell reached
      Selection.Offset(1, 0).Select
   Loop

   category = Selection.Value                          ' Set category
   industryCategory = Selection.Offset(0, 2).Value     ' Set industry category
   lifetime = Selection.Offset(0, 18).Value            ' Set lifetime
   depreciationPeriod = Selection.Offset(0, 19).Value  ' Set Depreciation Period
```

```
End Sub

Function findInputCell()

'Moves cursor to correct first input cell

   Selection.Offset(0, 20).Select         ' Move to the P&L headings column
   Do Until Selection.Value = "Basic NPV"  ' Move cursor down until NPV row reached
      Selection.Offset(1, 0).Select
   Loop
   Selection.Offset(0, 1).Select          ' Move cursor one cell to right

End Function

Function findTax(corporateTax, startYear, period)

'Finds and loads corporate tax rate data

   Sheets("Assumptions").Select                    'Go to Assumptions sheet
   If period = startYear Then Range("C19").Select _
   Else Selection.Offset(0, 1).Select              'If first year go to target cell otherwise shift from
previous cell
   corporateTax = Selection.Value                  'Capture value

End Function

Sub cashflowCalc(rowCounter, projectCapsules, cumulativeCF, yearCounter, interest, investment, _
      depreciation, corporateTax, depreciationPeriod, discountRate, lifetime, countTrials)

' Calculation of present value of future cashflows

Dim revenues As Single                          ' Define the Revenue variable

Do Until yearCounter = lifetime + 1                 ' Repeat for each year of the project lifetime

   revenues = Selection.Offset(-13, yearCounter - 1)   ' Capture revenues for given year
   ebitda = Selection.Offset(-7, yearCounter - 1)      ' Capture ebitda for given year
   carbonTax = Selection.Offset(-3, yearCounter - 1)   ' Capture carbon tax

   ' Capture depreciation which will be zero once fully depreciated

   If yearCounter <= depreciationPeriod Then _
      depreciation = Selection.Offset(-6, 0) _
      Else depreciation = 0

   ' Calculate tax based on pretax profit (zero if pretax is zero)

   If (ebitda - depreciation - interest) <= 0 Then _
      tax = 0 _
      Else tax = (ebitda - depreciation - interest) * corporateTax

   projectCapsules(rowCounter, yearCounter + 37, countTrials) = revenues   'Store revenues in the
projectCapsules array

   projectCapsules(rowCounter, yearCounter + 68, countTrials) = _
      ebitda - depreciation - interest - tax - carbonTax            'Store earnings in projectCapsules Array
```

```
   projectCapsules(rowCounter, yearCounter + 6, countTrials) = ebitda - tax - carbonTax 'Store CF in
projectCapsules Array

   cashflowPv = (ebitda - tax - carbonTax) / _
      (1 + discountRate(yearCounter)) ^ yearCounter   ' Calculate PV of Cash Flow

   cumulativeCF = cumulativeCF + cashflowPv           ' Calculate Cumulative PV Cash Flow

   yearCounter = yearCounter + 1                     ' Move to next period

Loop

End Sub

Sub calculateMean(projectCapsules, sheetCounter, caseFlag, numberTrials)

' Calculates the mean and SD of the outcome of the simulation

Dim count1 As Integer                      'Counts through number of plant variants
Dim count2 As Integer                      'Counts through project years
Dim sumofNPVTrials As Single               'Holds sum of all NPVs from trials
Dim sumofrevenueTrials As Single           'Holds sum of all revenue from trials
Dim sumoprofitTrials As Single             'Holds sum of all profits from trials
Dim statData(1 To 600, 1 To 6) As Single       'Holds mean and SD of NPV for each project year
Dim sumofNPVDeviations As Single           'Holds sum of the squares of all deviations from the
NPV mean (x(i) - mu(i)) ^ 2
Dim sumofrevenueDeviations As Single          'Holds sum of the squares of all deviations from the
revenue mean
Dim sumofprofitDeviations As Single           'Holds sum of the squares of all deviations from the
profit mean
Dim numberVariants As Integer              'Number of plant variants

If sheetCounter = 10 Then numberVariants = 13 Else numberVariants = 12  'Defines number of plant
variants for H2 and electricity cases

count1 = 0            'Set all variables to zero
count2 = 0
count3 = 0

sumofNPVTrials = 0         'Set variable
sumofrevenueTrials = 0      'Set variable
sumofNPVprofitTrials = 0    'Set variable
sumofNPVDeviations = 0      'Set variable
sumofrevenueDeviations = 0  'Set variable
sumofprofitDeviations = 0   'Set variable

' Calculate mean

For count1 = 1 To numberVariants       'Repeat for all plant variants

   For count2 = 1 To 43              'Repeat for all years

      For count3 = 1 To numberTrials  'Repeat for all trials

          sumofNPVTrials = projectCapsules(((count1 - 1) * 43 + count2), 5, count3) +
sumofNPVTrials          'Add next NPV to sum
          sumofrevenueTrials = projectCapsules(((count1 - 1) * 43 + count2), 47, count3) +
sumofrevenueTrials 'Add next revenue to sum
```

```
          sumofprofitTrials = projectCapsules(((count1 - 1) * 43 + count2), 78, count3) +
sumofprofitTrials   'Add next profit to sum

        Next

        statData(((count1 - 1) * 43 + count2), 1) = sumofNPVTrials / numberTrials  'Calculate mean of
NPV
        statData(((count1 - 1) * 43 + count2), 3) = sumofrevenueTrials / numberTrials  'Calculate mean
of revenue
        statData(((count1 - 1) * 43 + count2), 5) = sumofprofitTrials / numberTrials  'Calculate mean of
profit

        sumofNPVTrials = 0     'Reset variable
        sumofrevenueTrials = 0     'Reset variable
        sumofprofitTrials = 0     'Reset variable

    Next

Next

' Calculate StDev

For count1 = 1 To numberVariants        'Repeat for all plant variants

    For count2 = 1 To 43                'Repeat for all project years

        For count3 = 1 To numberTrials  'Repeat for all trials

        'Add current square of the deviation from the mean to previous sumofDeviations

            sumofNPVDeviations = (projectCapsules(((count1 - 1) * 43 + count2), 5, count3) - _
                statData(((count1 - 1) * 43 + count2), 1)) ^ 2 + sumofNPVDeviations
            sumofrevenueDeviations = (projectCapsules(((count1 - 1) * 43 + count2), 47, count3) - _
                statData(((count1 - 1) * 43 + count2), 3)) ^ 2 + sumofrevenueDeviations
            sumofprofitDeviations = (projectCapsules(((count1 - 1) * 43 + count2), 78, count3) - _
                statData(((count1 - 1) * 43 + count2), 5)) ^ 2 + sumofprofitDeviations

        Next

        statData(((count1 - 1) * 43 + count2), 2) = (sumofNPVDeviations / numberTrials) ^ 0.5
'Calculate SD
        statData(((count1 - 1) * 43 + count2), 4) = (sumofrevenueDeviations / numberTrials) ^ 0.5
        statData(((count1 - 1) * 43 + count2), 6) = (sumofprofitDeviations / numberTrials) ^ 0.5

        sumofNPVDeviations = 0 'Reset variable
        sumofrevenueDeviations = 0 'Reset variable
        sumofprofitDeviations = 0 'Reset variable

    Next

Next

displayResults sheetCounter, caseFlag, count1, count2, statData, numberVariants

End Sub

Sub displayResults(sheetCounter, caseFlag, count1, count2, statData, numberVariants)
```

```
'Outputs statistical data to appropriate sheet

Sheets(sheetCounter + 1).Select     'Go to output sheet
Range("B2").Select                  'Select top of years column

For count1 = 1 To numberVariants    'Repeat for all plant variants

   For count2 = 1 To 43             'Repeat for all project years

      Selection.Offset(1, 0).Select   'Move down one cell
      If count2 = 43 Then Selection.Offset(0, 1).Value = ""
      If count2 <> 43 Then
      Selection.Offset(0, 1 + caseFlag).Value = statData(((count1 - 1) * 43 + count2), 1) 'Ouput mean
1, 4, 7 or 10 cells to right depending on scenario
      Selection.Offset(0, 2 + caseFlag).Value = statData(((count1 - 1) * 43 + count2), 2) 'Output SD 2,
5, 8 or 11 cells to right depending on scenario
      Selection.Offset(0, 3 + caseFlag).Value = statData(((count1 - 1) * 43 + count2), 3)
      Selection.Offset(0, 4 + caseFlag).Value = statData(((count1 - 1) * 43 + count2), 4)
      Selection.Offset(0, 5 + caseFlag).Value = statData(((count1 - 1) * 43 + count2), 5)
      Selection.Offset(0, 6 + caseFlag).Value = statData(((count1 - 1) * 43 + count2), 6)
      End If

   Next

Next

End Sub
```

# 7.2 Details of Existing Electricity Generating Plant

## Coal plant

**Built**

| | Capacity (MW) | Load Factor (Est.) | Output (GWh) | Availability factor | "Unused" Production | Operator |
|---|---|---|---|---|---|---|
| Cockenzie | 1152 | 43% | 4,300 | 90% | 4,782 | SPW |
| Long Gannet | 2304 | 43% | 8,600 | 90% | 9,565 | SPW |
| **Total** | **3456** | | **12,900** | | **14,347** | |

**Load Factors**

| | DUKES (2006 Digest) | | SPW - Iberdrola Merger Doc |
|---|---|---|---|
| | 2005 | 2001 - 2005 | 2005 / 06 |
| Conventional Therr | 46.3% | 44.0% | |
| of which Coal | 63.6% | 60.6% | 43% |

## Gas plant

**Built**

| | Capacity (MW) | Load Factor (Est.) | Output (GWh) | Availability Factor | "Unused" Production | Operator | |
|---|---|---|---|---|---|---|---|
| Peterhead | 2319 | 44% | 8,904 | 95% | 10,395 | SSE | Note: This figure is much lower than for other plant since Peterhead is capacity constrained from 2,319MW to 1,540MW |
| Fife | 120 | 66% | 689 | 95% | 310 | SSE | |
| **Total** | **2439** | | **9,592** | | **10,705** | | |

**Load Factors**

| | DUKES (2006 Digest) | | SPW - Iberdrola Merger Doc |
|---|---|---|---|
| | 2005 | 2001 - 2005 | 2005 / 06 |
| CCGT | 59.6% | 65.5% | 58% |

## Nuclear Plant

**Built**

| | Capacity (MW) | Load Factor (Est.) | Output (GWh) | Availability Factor | "Unused" Production | Operator |
|---|---|---|---|---|---|---|
| Hunterston B | 1,190 | 71% | 7,388 | 84% | 1,368 | British Ener |
| Torness | 1,250 | 71% | 7,761 | 84% | 1,437 | British Ener |
| Totals | 2,440 | | 15,149 | | 2,806 | |

**Load Factors**

| | DUKES (2006 Digest) | | British Energy Annual | |
|---|---|---|---|---|
| | 2005 | 2001 - 2005 | 2006 / 07 | 5 Year Average |
| Nuclear | 72.4% | 74.6% | | |
| Overall | | | 61% | 72% |
| Hunterston B | | | 33% | 70% |
| Torness | | | 69% | 72% |
| Overall Scotland | | | 51.2% | 70.9% |

## Wind Plant

**Built**

| | Capacity (MW) | Load Factor (Est.) | Output (GWh) | Operator |
|---|---|---|---|---|
| Ardrossan | 24 | 32% | 68 | Airtricity |
| Bein Ghlas | 8 | 32% | 23 | Beaufort Wind |
| Causeymire | 48 | 32% | 136 | Beaufort Wind |
| Novar | 17 | 32% | 48 | Beaufort Wind |
| Windy Standard | 22 | 32% | 62 | Beaufort Wind |
| Crystal Rig | 50 | 32% | 141 | Crystal Rig |
| Bowbeat | 16 | 32% | 45 | Eon |
| Deucheran Hill | 3 | 32% | 8 | Eon |
| Paul's Hill | 55 | 32% | 155 | Paul's Hill |
| Rothes | 51 | 32% | 144 | Rothes Wind |
| Artfield Fell | 20 | 32% | 57 | SSE |
| Hadyard Hill | 120 | 32% | 339 | SSE |
| Spurness | 8 | 32% | 23 | SSE |
| Tangy | 13 | 32% | 37 | SSE |
| Bein an Tuirc | 30 | 32% | 85 | SPW |
| Coal Clough | 10 | 32% | 28 | SPW |
| Cruach Mhor | 30 | 32% | 85 | SPW |
| Dun Law | 17 | 32% | 48 | SPW |
| Hagshaw Hill | 16 | 32% | 45 | SPW |
| Hare Hill | 13 | 32% | 37 | SPW |
| **Total** | **571** | | **1,613** | |

**Additional from BWEA**

| | | | |
|---|---|---|---|
| Crystal Rig 1a | 13 | 32% | 35 |
| Wether Hill | 18 | 32% | 51 |
| Dummuie | 10 | 32% | 29 |
| Black Hill | 29 | 32% | 81 |
| Braes o' Doune | 72 | 32% | 203 |
| Black Law B | 28 | 32% | 78 |
| Beinn Tharsuinn | 30 | 32% | 85 |
| Wardlaw Wood | 18 | 32% | 51 |
| Farr | 92 | 32% | 260 |
| Black Law A | 97 | 32% | 274 |
| Burray | 1 | 32% | 2 |
| Forss, Hill of Lipste | 2 | 32% | 7 |
| Burra Dale (Ext) | 2 | 32% | 5 |
| Findhorn | 1 | 32% | 2 |
| Thorfinn, Orkney | 3 | 32% | 8 |
| Myres Hill | 2 | 32% | 5 |
| Sigurd | 1 | 32% | 4 |
| Burra Dale | 2 | 32% | 6 |
| Gigha | 1 | 32% | 2 |
| Glens of Foudland | 26 | 32% | 73 |
| Boulfruich | 13 | 32% | 37 |
| Boyndie Airfield | 22 | 32% | 62 |
| | **481** | | **1,360** |
| Total | **1052** | | **2973** |

**Under Construction**

| | Capacity (MW) | Load Factor (Est.) | Output (GWh) |
|---|---|---|---|
| Craig | 8 | 32% | 23 |
| Minsca | 37 | 32% | 104 |
| Robin Rigg A+B | 180 | 32% | 509 |
| Dalwinston | 30 | 32% | 85 |
| Eaglesham | 322 | 32% | 910 |
| Tangy + | 6 | 32% | 17 |
| Fintry | 3 | 32% | 7 |
| Earlsburn | 38 | 32% | 106 |
| Green Knowes | 32 | 32% | 89 |
| Ardinglass | 16 | 32% | 44 |
| Drumderg | 37 | 32% | 104 |
| Millenium | 40 | 32% | 113 |
| Ben Aketil | 23 | 32% | 65 |
| Arnish Moor | 4 | 32% | 11 |
| Kilbraur | 48 | 32% | 134 |
| Forss + | 5 | 32% | 15 |
| Beatrice | 10 | 32% | 28 |
| **Total** | **836** | | **2,363** |

**Load Factors**

| | Ofgem Statistics |
|---|---|
| Wind - UK Average Onshore | 28.4% |
| Scotland - Lowlands | 31.5% |
| Scotland - C, O, S | 33.0% |
| Average Scotland Onshore | 32.3% |
| Shetland | 65.0% |
| Wind - UK Average Offshore | 32.6% |

# Diesel Plant

**Built**

| | Capacity (MW) | Load Factor (Est.) | Output (GWh) | Availability Factor | "Unused" Production | Operator |
|---|---|---|---|---|---|---|
| Arnish | 3 | 66% | 17 | 90% | 6 | SSE |
| Barra | 2 | 66% | 12 | 90% | 4 | SSE |
| Bowmore | 6 | 66% | 35 | 90% | 13 | SSE |
| Kirkwall | 16 | 66% | 93 | 90% | 34 | SSE |
| Lerwick | 67 | 66% | 387 | 90% | 141 | SSE |
| South Uist | 12 | 66% | 69 | 90% | 25 | SSE |
| Stornoway | 24 | 66% | 139 | 90% | 50 | SSE |
| Tiree | 3 | 66% | 17 | 90% | 6 | SSE |
| | 133 | | 769 | | 280 | |

No data on Load Factor - assumed to be approximately as per gas plant

# Hydro Plant

**Built**

| Hydro Plants in Scotland | Capacity (MW) | Load Factor | Output (GWh) | Availability Factor | "Unused" Production | Operator |
|---|---|---|---|---|---|---|
| Fort William | 62 | 31% | 170 | 95% | 346 | Alcan |
| Kinlochleven | 19.5 | 31% | 53 | 95% | 109 | Alcan |
| Braevallich | 2 | 31% | 5 | 95% | 11 | RWE |
| Garrogie | 2 | 31% | 5 | 95% | 11 | RWE |
| Inverbain | 1 | 31% | 3 | 95% | 6 | RWE |
| Affric / Beauly | 176.4 | 31% | 482 | 95% | 986 | SSE |
| Breadalbane | 103 | 31% | 282 | 95% | 575 | SSE |
| Conon | 108 | 31% | 295 | 95% | 603 | SSE |
| Great Glen | 122 | 31% | 334 | 95% | 682 | SSE |
| Shin | 33 | 31% | 90 | 95% | 184 | SSE |
| Sloy / Awe | 316 | 31% | 864 | 95% | 1,766 | SSE |
| Tummel | 242 | 31% | 662 | 95% | 1,352 | SSE |
| Chliostair | 1 | 31% | 3 | 95% | 6 | SSE |
| Cuileag | 3 | 31% | 8 | 95% | 17 | SSE |
| Kerry Falls | 1 | 31% | 3 | 95% | 6 | SSE |
| Loch Dubh | 1 | 31% | 3 | 95% | 6 | SSE |
| Nostie Bridge | 1 | 31% | 3 | 95% | 6 | SSE |
| Storr Lochs | 2 | 31% | 5 | 95% | 11 | SSE |
| Galloway | 109 | 31% | 298 | 95% | 609 | SPW |
| Lanark | 17 | 31% | 46 | 95% | 95 | SPW |
| **Totals** | **1321.9** | | **3,615** | | **7,386** | |
| **Under Construction** | | | | | | |
| Glen Doe | 100 | 31% | 273 | 95% | 559 | SSE |
| Total | 100 | | 273 | | 559 | |
| **Pumped Storage** | | | | | | |
| Foyors | 300 | 11% | 278 | NM | | SSE |
| Cruachan | 440 | 11% | 408 | NM | | SPW |
| Total | 740 | | | | | |

### 7.3 Share Price Graphs

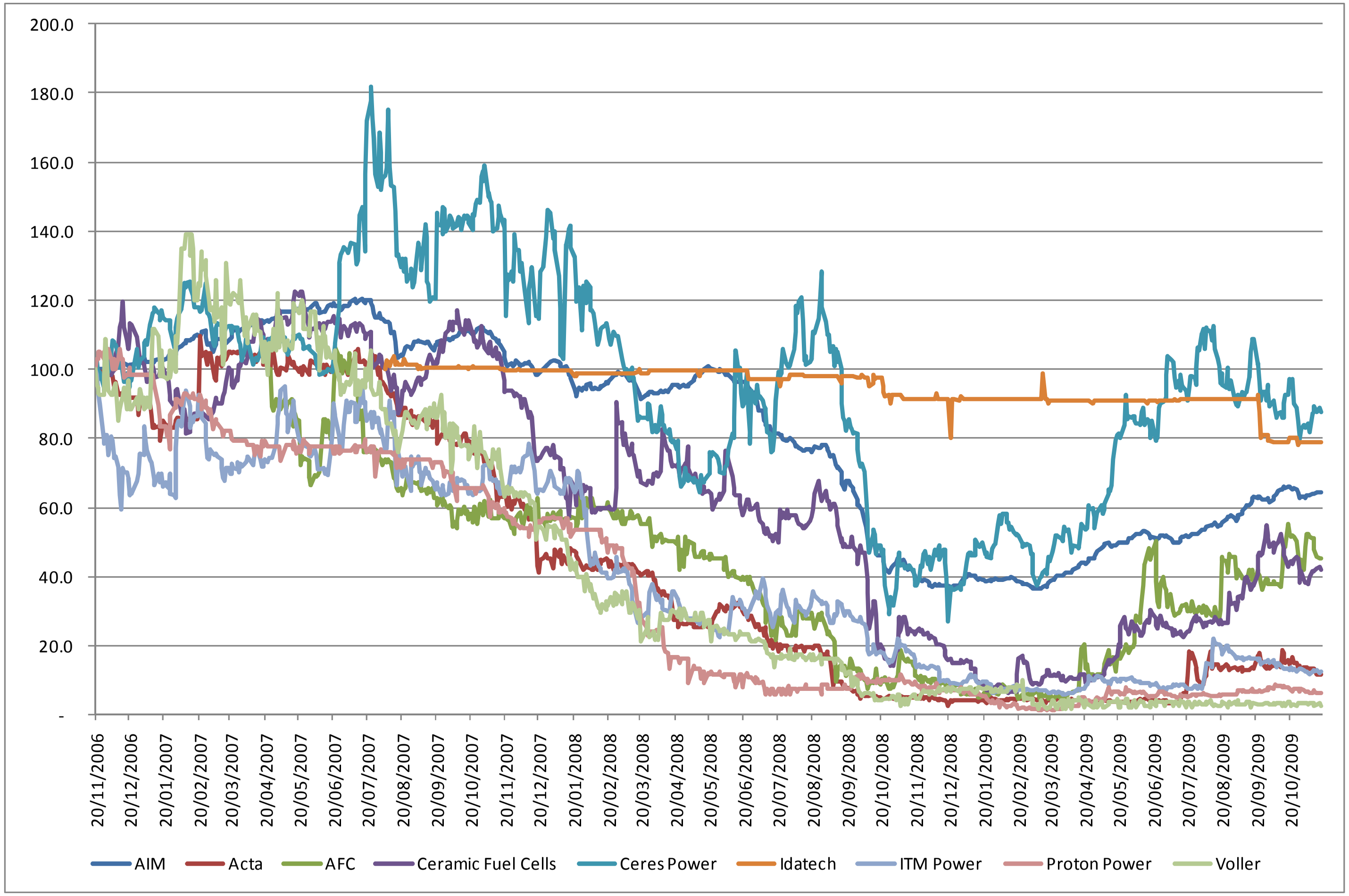



**Figure 7.1 Share Price Performance of UK Listed Hydrogen and Fuel Cell Companies against AIM (Nov 06 – Oct 09)**

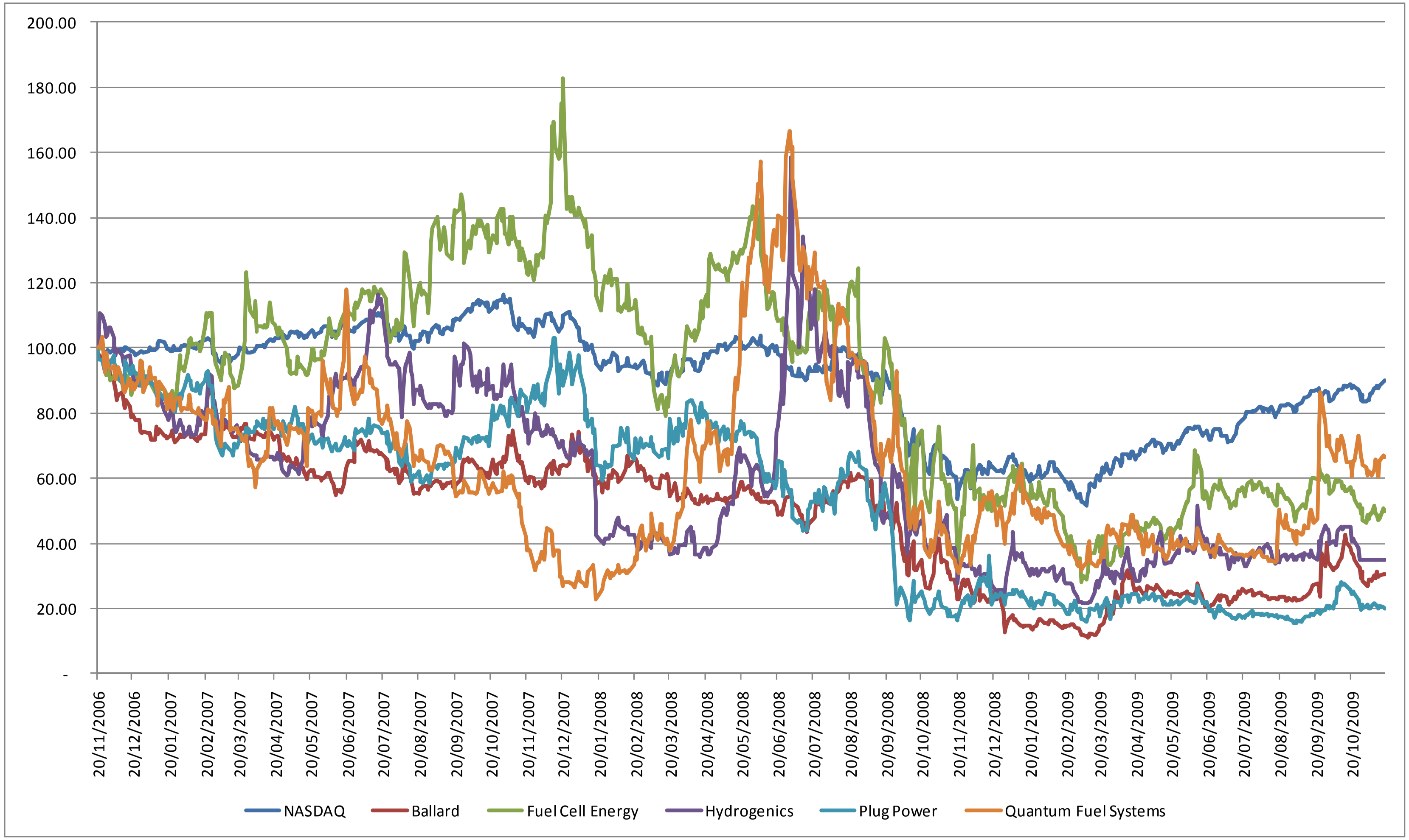



**Figure 7.2 Share Price Performance of North American Hydrogen and Fuel Cell Companies against NASDAQ (Nov 06 – Oct 09)**

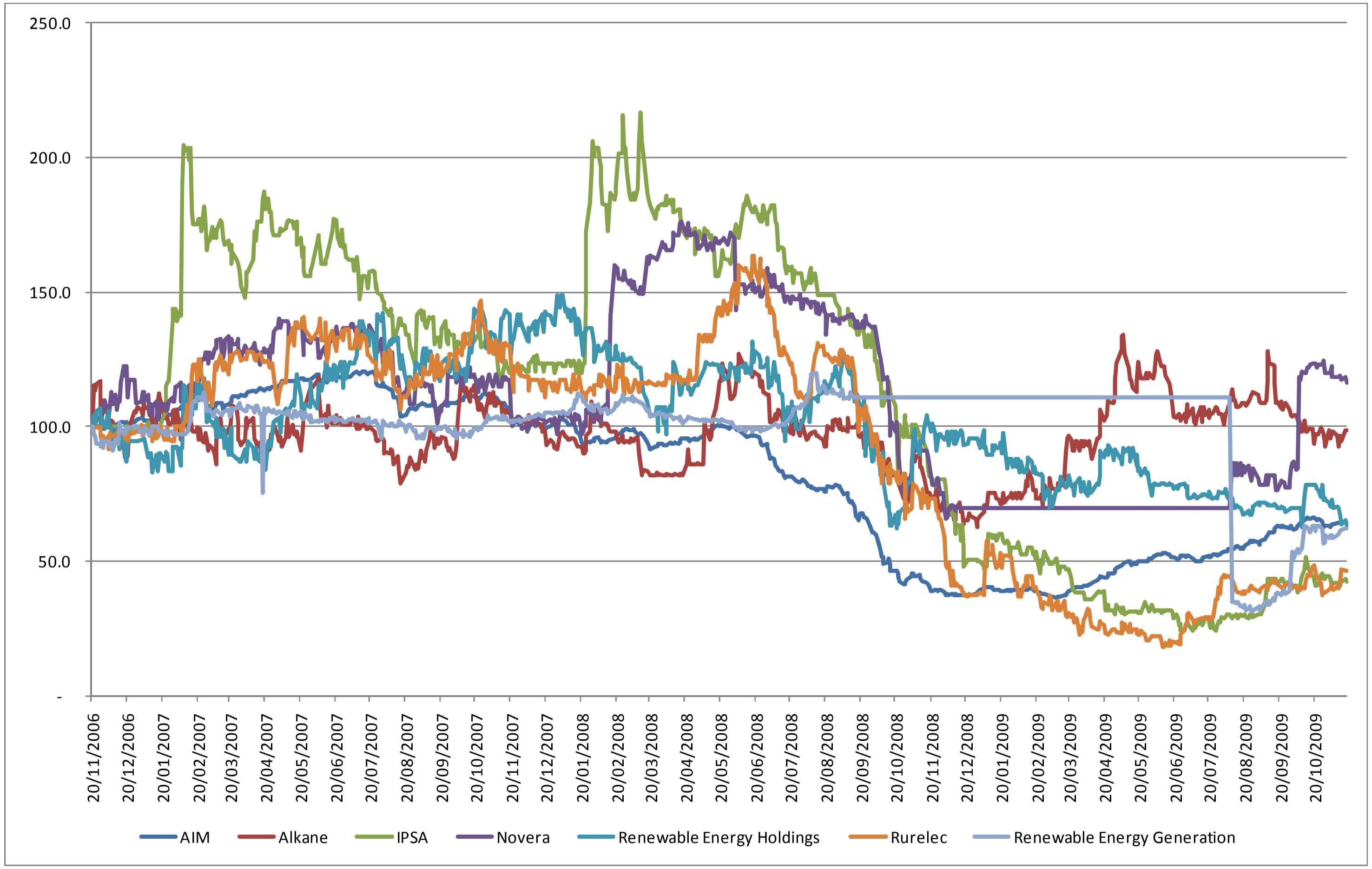



**Figure 7.3 Share Price Performance of UK Renewable Energy Utilities Against AIM (Nov 06 – Oct 09)**

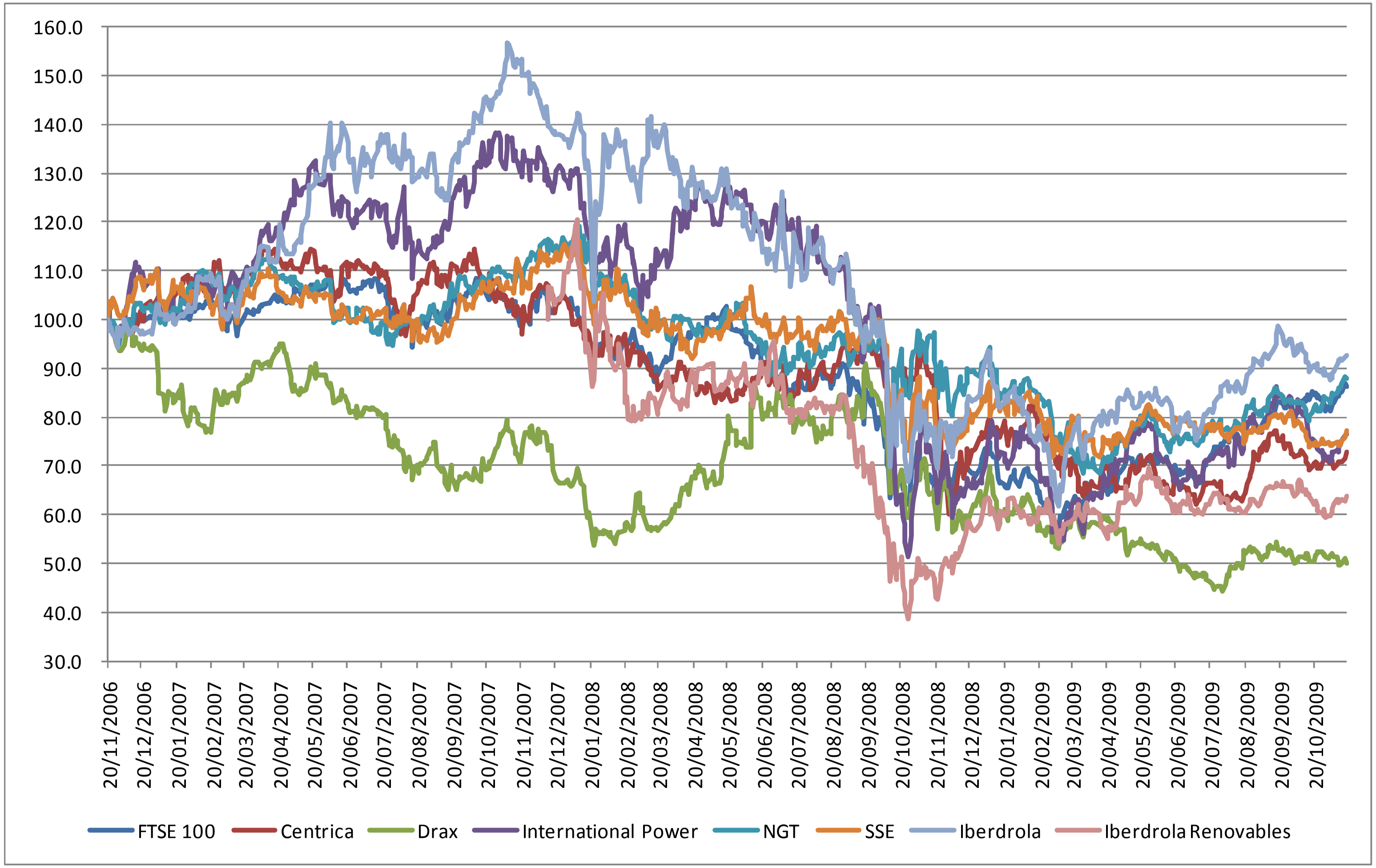



**Figure 7.4 Share Price Performance of UK Utilities Against FTSE 100 (Nov 06 – Oct 09)**

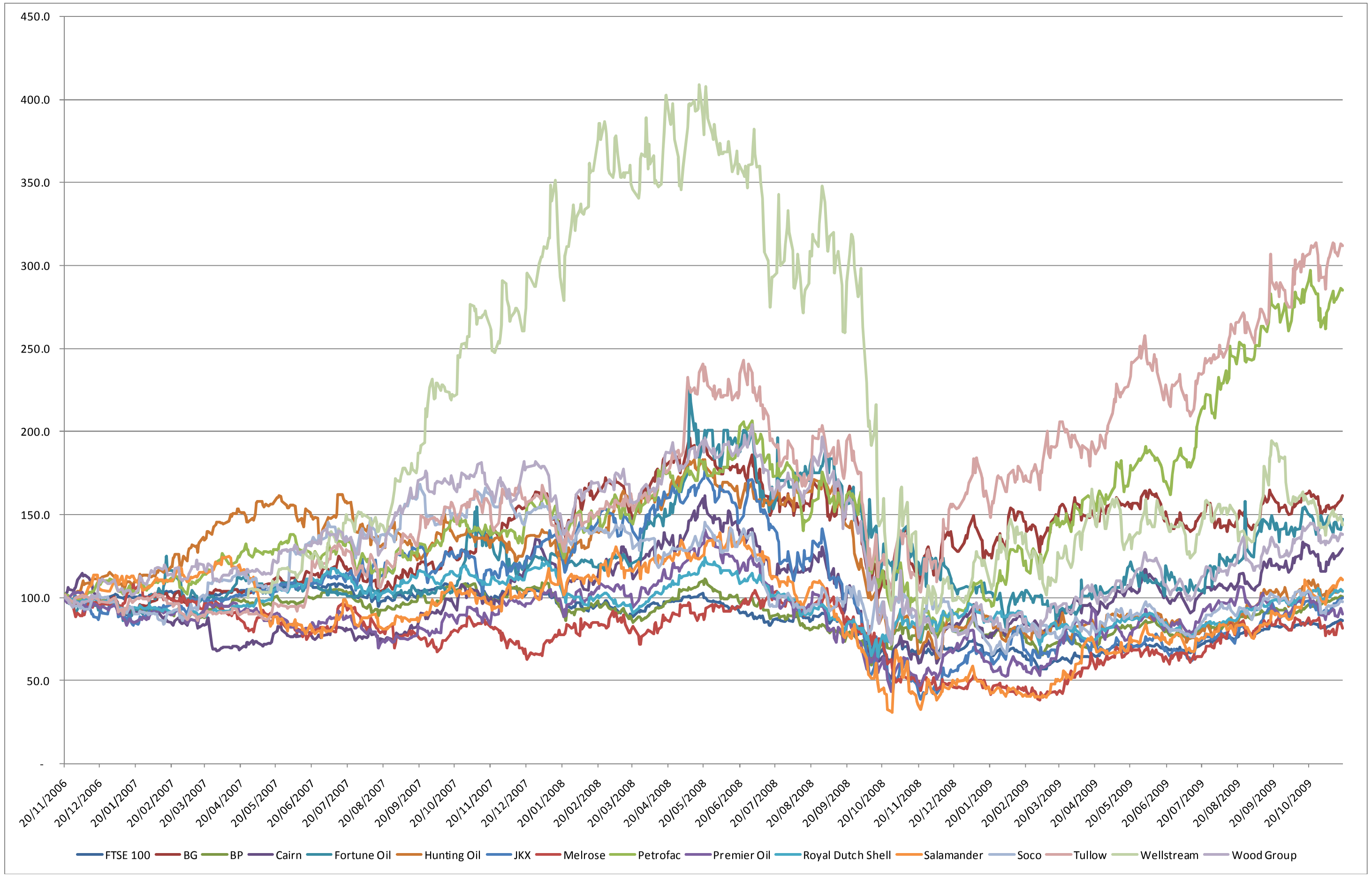



**Figure 7.5 Share Price Performance of UK Oil and Gas Companies Against FTSE 100 (Nov 06 – Oct 09)**

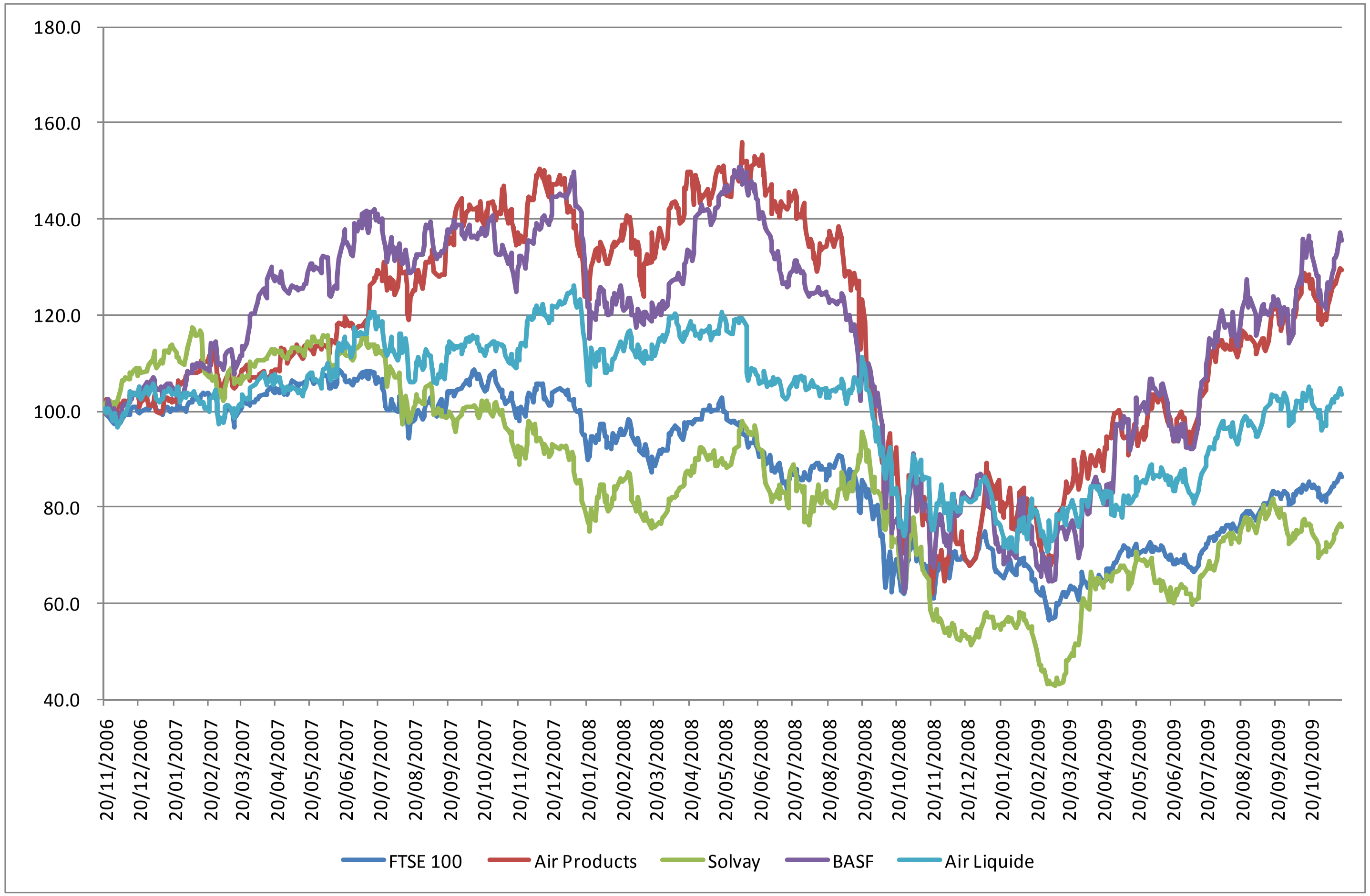



**Figure 7.6 Share Price Performance of International Industrial Gases Companies Against FTSE 100 (Nov 06 – Oct 09)**

## 7.4 Glossary

| | |
|---|---|
| AD | Anaerobic Digester, being a device in which hydrogen or methane is produced from organic matter. |
| BERR | Department for Business, Energy and Regulatory Reform. |
| BEV | Battery Electric Vehicles, being vehicles powered by electric motors and having battery storage. |
| BVE | Book value of equity, being the nominal value of a company's shares based on their face value (as opposed to market value) |
| BVL | Book value of liabilities, being the nominal value of a company's liabilities. |
| CAPM | Capital Asset Pricing Model which describes the relationship between the price volatility of a given security and the expected return on that security. |
| Cash flow | The cash received in a given period from a given project or business activity. Approximates to EBITDA. |
| CCA | Climate Change Agreement, being an opt-out from the CCL in exchange for a company taking measures to reduce carbon |
| CCL | Climate Change Levy, being an end-user tax on carbon emissions |
| CCS | Carbon Capture and Storage |
| COE | Compensation of Employees, being the sum of all employee salaries. |
| Correlation | The degree to which the changes in the value of two variables are related. |
| DCF | Discounted Cash Flow analysis |
| DECC | Department for Energy and Climate Change. |
| E(r) | Expected return on an equity, being the mean return on a |

| | |
|---|---|
| | given share. |
| $E(r_m)$ | Expected (or mean) return on the market |
| Earnings / Profits | The receipts of a company after tax and before any distribution of dividends to shareholders |
| EBIT | Earnings Before Interest and Tax, being the receipts of a company before the deduction of interest payments on loans and tax. |
| EBITDA | Earnings Before Interest Tax and Amortisation, being the receipts of a company before the deduction of interest payments on loans, tax, depreciation charges relating to physical assets of the company and amortisation on its intangible assets. |
| EFOM | Energy Flow Optimisation Model |
| EPS | Earnings per Share, being the Earnings divided by the number of shares outstanding (either nominal or fully diluted). |
| Equity Market Capitalisation | The value of a company's equity, defined as the number of shares (nominal or fully diluted) multiplied by the market price of the share. |
| ESI | Electricity Supply Industry |
| EU ETS | European Union Emissions Trading Scheme, being the principal market on which carbon credits are traded in Europe. |
| EUA Carbon Futures | Futures contract for the purchase of carbon credits |
| EUR | Euros |
| EV | Enterprise Value defined as the Equity Market Capitalisation plus the value of the structural interest bearing debt (either book or market, according to the case. |
| FCV | Fuel cell Vehicles, being vehicles powered by electric motors |

| | |
|---|---|
| | for which the electricity is supplied form a fuel cell which in turn is supplied either by a store of pure hydrogen or a hydrocarbon. |
| FIT | Feed-in-Tariff, being a guaranteed price available to small scale renewable electricity producers. |
| FP6 | $6^{th}$ edition of the EU framework funding for research |
| FTSE 100 | The market index of the 100 largest companies quoted on the LSE Main List |
| Fully Diluted | Refers to the total share capital of a company once all options over the company's shares are included. |
| G8 | Group of 8 industrialised nations (Canada, France, Germany, Italy, Japan, Russian Federation, UK and USA). |
| GBP | British Pounds |
| GDP | Gross Domestic Product, being a measure of a country's economic activity. |
| GEP | Generation Expansion Planning |
| GMI | Gross Mixed Income, roughly equivalent to the cash profits from all small businesses. |
| GOS | Gross Operating Surplus, roughly equivalent to the cash profits from all large businesses. |
| GW / GWh | Gigawatts ($10^9$) / Gigawatt hours |
| $H_2FC$ | Hydrogen and fuel cells (industry, sector etc as applicable) |
| Hythane | Mixture of hydrogen and natural gas in the ratio 25% hydrogen to 75% natural gas |
| IAEA | International Atomic Energy Agency |
| ICEPT | Imperial College Centre for Energy Policy and Technology |
| IEA | International Energy Agency |
| IPCC | International Panel on Climate Change |

| | |
|---|---|
| kW / kWh | Kilowatts ($10^3$) / Kilowatt hours |
| LEAP | Long-Range Energy Alternatives Planning. |
| Leverage | The ratio of the value (either book or market, according to the case) of a company's structural long term debt (i.e. debt which forms part of the company's main capital structure) to the market value of a company's equity. |
| LHV | Lower Heating Value, defined as the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 25 °C. |
| LIBOR | London Interbank Offered Rate, being the interest rate being the rate charged on lending is a daily reference rate based on the interest rates at which banks borrow unsecured funds from other banks in the London wholesale money market (or interbank market). |
| LSE AIM | The Alternative Investment Market of the London Stock Exchange where typically smaller, growth stage companies are listed. |
| LSE Main List | The main section of the London Stock Exchange typically where larger and more mature companies are listed. |
| LTM | Last Twelve Months, being the latest twelve month period for which data is available. |
| MAC | Marginal Abatement Curve |
| MAED | Model for Analysis of Energy Demand. |
| MARKAL | Market Allocation Model. |
| ME | Market Equity (see Equity Market Capitalisation) |
| MESSAGE | Model for Energy Supply Systems Alternatives and their General Environmental impact |
| MODEST | Modelling and Optimization of District Heating and |

| | |
|---|---|
| | Industrial Energy System |
| Monte Carlo Simulation | A class of computational algorithms that rely on repeated random sampling to compute their results. |
| MOREHys | Model for Optimisation of Regional Hydrogen Supply |
| MVPT | Multi-Variate Portfolio Theory |
| MW / MWh | Megawatts ($10^6$) / Megawatt hours |
| NASDAQ | One of three main US stock markets, the others being the New York Stock Exchange and the American Stock Exchange. NASDAQ has typically been the preferred market of technology companies. |
| NORMINV | A function in Excel which based on the input of a random number returns a value fitting a Normal probability distribution based on a defined mean and standard deviation. |
| NPV | Net Present Value, being the sum of all Cash flows over the lifetime of a business activity or project discounted to their present value by an appropriate discount rate, less the initial investment cost. |
| O&M | Operation and maintenance |
| OECD | Organisation for Economic Cooperation and Development. |
| PE ratio | Price to earnings ratio, being the ratio between the price of a share and the earnings per share in a given period usually the latest 12 month period (historical PE) or, the expected EPS of the next period (Forward PE). |
| POLES | Prospective Outlook on Long-term Energy Systems |
| Price Elasticity | The variation of demand to changes in price |
| PSI | Policy Studies Institute |
| Q | A measure of the extent to which a company’s Equity Market Capitalisation exceeds its book value. |
| RE | Renewable electricity generation |

| | |
|---|---|
| Revenues / Sales | The total receipts of the company |
| $R_f$ | Risk free rate of return, being the return on an asset for which the return is certain, usually taken to be the return on a Government Bond |
| RO | Renewable Obligation, being the requirement placed on an electricity generator to supply a proportion of its overall power from renewable sources. |
| ROC | Renewable Obligation Certificate, being a certificate earned in exchange for the production of 1 MWh of renewable electricity which can in turn be traded. |
| ROE | Return on Equity being the sum of all profits accruing to the holders of equity in a company |
| RPI + X – Y | Retail Price Index + X – Y. Formula used to calculate permitted price increases by regulated generators under the privatisation of the UK ESI where X is an efficiency factor and Y an allowance for capital investment. |
| RTFO | Renewable Transport Fuel Obligation, being the requirement placed on transport fuel provider to supply a proportion of its overall fuel from renewable sources. |
| SMR | Steam Methane Reforming, being the process of producing hydrogen (and $CO_2$) from natural gas using heat and steam in a shift process. |
| STP | Standard Temperature and Pressure being a temperature of 0ºC and 1 atmosphere |
| TCO | Total Cost of Ownership |
| TOC | Transport Obligation Certificate, being a certificate earned in exchange for the delivery of 1 litre of renewable transport fuel which can in turn be traded. |
| TW / TWh | Terrawatt ($10^{12}$) / Terrawatt hours |

| | |
|---|---|
| UKCS | UK Continental Shelf, being the area of the North Sea off the coast of the British Isles where oil and gas are produced. |
| UKSHEC | UK Sustainable Hydrogen Energy Consortium is one of a series of energy research projects supported by the EPSRC's Sustainable Power Generation and Supply initiative (SUPERGEN). |
| USD | United States Dollars |
| WACC | Weighted Average Cost of Capital |
| WASP | Wien Automatic System Planning Package. |
| WWEA | World Wind Energy Association |
| β | Measure of the sensitivity of the expected returns on a given share of equity to changes in the expected return on the relevant stock market |

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