Electricity Investment Behavior in Response to Climate Policy Risk

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Abstract: We analyze the effects of climate policy and regulatory risk on investment behaviour in the electricity sector. Using a multistage stochastic optimization model with uncertainty in carbon price, we demonstrate that financial details with real options and uncertainties can make substantial difference compared to the basic economic net present value evaluation. We also show that this approach is necessary to capture important details for reliable economic policy decisions. Thus, the effects of various carbon policies and market instruments on investment will depend on the characteristics of the companies, but appear to promote a less competitive market structure as well as path-dependent technology change. Our experiments identify that risk averse investors may, surprisingly under certain circumstances, invest before risk neutral investors and that rapid carbon capture and storage technology adoption rates can encourage investments even in non fossil technologies.

Keywords: Carbon Policy, Investment Behaviour, Stochastic Optimization, Electricity Sector

1. Introduction

Understanding the interaction of institutional policies and corporate behaviour creates substantial modelling challenges, especially when Governments are seeking to create new economic initiatives and market instruments. Stylised models of economic theory often do not have sufficient detail for realistic analysis, econometric analysis will not be possible if relevant time series do not exist, and behavioural considerations of risk aversion and agent heterogeneity may render classical analysis based upon markets with homogeneous, risk neutral players too simplistic. In such contexts, policy analysis through a computationally intensive, behavioural model is often the most appealing methodology. This seems, particularly, to be the context when seeking to analyse the new market-based instruments to mitigate global warming. Many regional and state institutions are formulating policies that will change the operations of, and investment in, fossil fuel energy facilities. The European Union has had a mandatory cap-and-trade market for carbon dioxide emissions in the power and heavy industry sectors since 2005, with the ambitious post-Kyoto target of a 20% reduction by 2020 and much more by 2050, depending upon international accords (BERR 2008, European Commission 2008). Other regions, countries and states are following (Labatt and White 2007). Yet, how effective these, and other policies, will be in influencing corporate behaviour, and thereby achieving the climate goals, is clearly a crucial concern not only to the policy-makers but also to the companies operating strategically within those markets.

As an externality to economic activities, global warming is quite different even to air pollution. The benefits of air pollution controls accrue locally and regulations often set a credible framework within which companies need to adapt their operations (eg the US Sulphur Dioxide cap and trade initiative since 1995; Ellerman et al. 2000). Global warming is truly global, however, in that the benefits only materialise through substantial international co-operation, and so there are policy risks of a higher order than the usual, notwithstanding extensive, regulatory risks to be faced by the energy sector. Apart from the fragility of multiregional accords and the burden sharing agreements, there is uncertainty in the feasibility of targets, the social willingness to pay as well as the actual effectiveness of the economic and technological implementations, all of which motivate governments to maintain flexibility in their carbon mitigation measures.

Policy risk is therefore an important ingredient in the investment decision-making of the companies affected by carbon trading. Whenever carbon policies get reset periodically, a real options analysis can indicate a propensity to delay investments, possibly depending upon the technologies (Reedman et al. 2006, Blyth et al. 2007), with nuclear in particular having different optionalities compared to coal and gas (Roques et al. 2006, Rothwell 2006). Anecdotal industry comments also tend to corroborate this theoretical view that carbon policy risk inhibits investment (eg Gribben 2008). Whilst the straightforward option to delay follows analytically from a risk neutral decision analysis (Dixit and Pindyck 1994), it is apparent that investment in power generation will exhibit some degree of risk aversion and that modelling this behavioural element may be a delicate process (Ishii and Yan 2004). In practice, it seems that companies consider risk constraints within their financial planning models for investment, possibly in terms of risk metrics for cash-flow-at-risk (Froot et al. 1993, Denton et al. 2003, Minton and Schrand 1999, LaGattuta et al. 2001), but mainly in preserving the financial ratios necessary to maintain their investment grades with the credit rating agencies (Hempstead et al. 2007). In Section 4 below, we develop a number of specific propositions related to the relative propensity of companies to invest, in the short or medium term, in particular power generating technologies depending upon several factors related to the nature of carbon price risks, how often Governments revise targets or set caps and floors, the companies' own attitudes to risk, the nature of their financial exposures, and their existing portfolio asset base of technologies.

In more specific terms, whilst it is clear that the mandatory requirement to cover carbon emissions from fossil fuel plants increases their marginal costs by the value of these carbon allowances, how uncertainty in carbon prices affects investment in different technologies has subtle implications. Since costs get passed through into the wholesale markets (Fezzi and Bunn 2008), if the fossil fuel plant, gas and coal, are the marginal price-setters in the market, it may seem that carbon price uncertainty will not affect investment in the carbon emitting plant, if it is financially viable, as much as in the infra marginal, possibly more capital-intensive, non carbon emitting plant, such as nuclear. This then raises the questions of whether risk aversion will have a larger effect on the non-fossil technologies, and how Government policies to reduce risks will affect different technologies. If it is apparent that there is a substantial difference in the propensities to invest between the risk averse and the risk neutral, and also between the project and equity financed participants, then, apart from the level of carbon prices per se, the associated policy risk will have an effect on market structure evolution and the tendency for investment to be led by dominant incumbents rather than new independent power producers. This will be further enhanced if the resource-base benefits of a portfolio of existing facilities increase the propensity to invest.

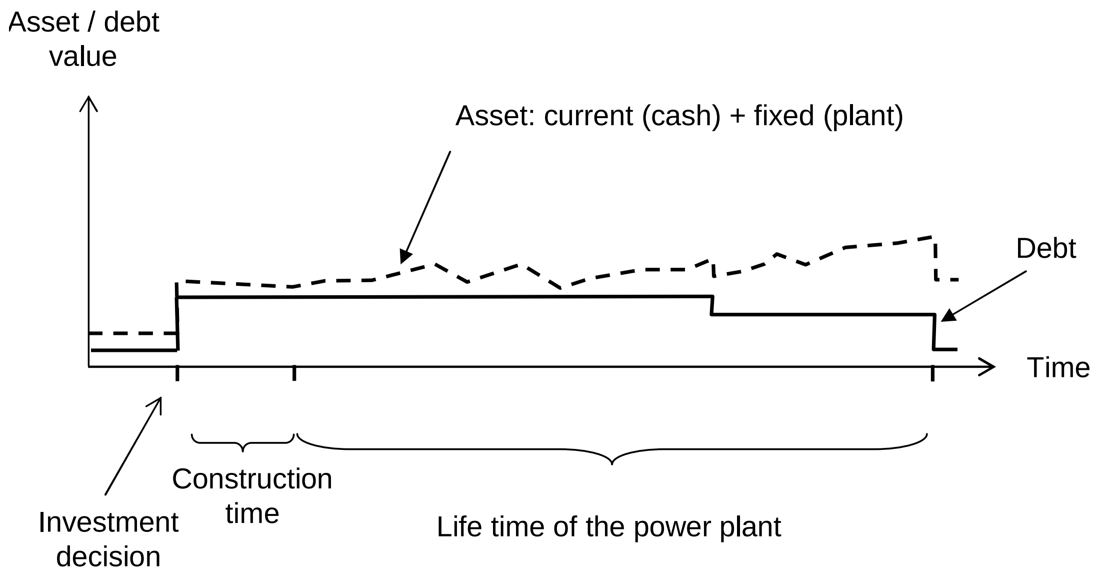
To create experimental insights into these propositions, a rather more precise computational investment model is developed, than is usually the case in economic policy analyses. Energy policy models for capacity investment typically assume that new plant will be built whenever there is a positive net present value (Caramis 1982, Schumacher and Sands 2006), yet this would be inadequate to reflect any importance placed upon risk constraints. Furthermore, basic economic net present value calculations do not evaluate financial planning considerations such as optimising the debt exposures in the investment plans. We therefore specify a multistage stochastic optimisation model to deal with these features and to evaluate the investment opportunities. Whilst stochastic optimisation in this context is not new (Birge and Rose 1995, Birge and Louveaux 1997), we incorporate a new scenario generation approach, risk constraints and a more detailed level of financial planning into the methodology. This also allows us to compute specific cumulative probabilities of investment by a particular date, thereby focussing more precisely, than in previous real options analyses, upon the way that policy risk, under various assumptions, inhibits investment. At a time when some Governments are at least as concerned about resource adequacy as carbon abatement, developing a precise analytical focus upon the relative probabilities of investment, over time, and their policy drivers, would appear to have considerable economic relevance.

In focusing specifically on the impact of carbon policy risk upon the temporal cumulative probability function of investment, we do not seek to address the issue of technology choice, nor optimal capacity expansion. Rather, we envisage a company considering the investment decision in a new power plant of a particular technology and consider whether carbon policies, financial considerations, existing asset portfolio and risk attitudes would increase or decrease the probability of investment by a particular date, and how their relative effects emerge. Whilst a general economic perspective might view an industry with homogeneous agents each willing to invest in any technology, we take the observation that the industry is heterogeneous and that, providing an investment is financially attractive, companies will pursue technologies with which they have experience or to which they are strategically attracted. We do not, therefore, engage in a discussion of whether one technology or another is the most preferred, and even from an economic perspective that is so dependent upon fuel and construction assumptions that change rapidly (Milborrow 2008). We do, however, address questions of whether carbon policies and other factors affect different technologies to a relatively different extent. Nor do we address, for the same reason the issue of the optimal capacity mix for carbon mitigation (Roques et al. 2006, Grubb et al. 2005, Green 2007), except insofar as identifying the effect that an existing technology portfolio might have on a singular new investment.

The research contributions of the experiments are both reassuring and surprising. First, we show that incorporating financial details together with real options and uncertainty can make significant differences in the evaluations of the investments beyond the basic economic net present value formulation. Thus, we show that capturing the important corporate aspects of behaviour is important in the policy modelling. As regards the policy risk exposure, the impacts do vary by technology and financial strength, suggesting that policy risk may affect the evolution of market structure. Larger, financially stronger, and more diversified incumbent players can accommodate policy risks better than new, project-financed independent power producers, suggesting a tendency for carbon policies to make the markets less competitive. Further, policy variations such as caps, floors, or free emission allocations for new plants do make a difference, again depending upon technology and corporate behaviour. The surprises which emerged, however, reinforced the value of computational economics in addressing this problem, as it is clear that in assessing the relative effects of policy risk and instruments, the "devil" is indeed often in the detail. For example, whilst one might expect the risk averse participants to always invest later than the risk neutral, we find the opposite occurs for coal if the power sector is quite profitable, or for coal and gas if their cost of capital is relatively low, and just as surprising, that increased price volatility may encourage investment by risk averse gas generators. We also observe that a breakthrough in Carbon Capture and Storage for coal and gas plants may actually encourage investment in the competing technology, nuclear. We develop the intuition behind these observations in Section 4, but such subtle policy-agent interactions would not have become evident without the precise focus and computational detail in the model.

The paper is organized as follows. Section 2 formulates the carbon risk investment setting and Section 3 describes the computational model. Section 4 motivates the experimental propositions and comments upon the results. Section 5 concludes.

Figure 1 Power plant investment and the value of asset (dashed line) and debt (solid line)



2. The Stylised Investment Framework

We focus upon the two heavy carbon-emitting technologies, coal and gas, where carbon trading will directly influence operational costs and investment. We also consider a non-fossil capital intensive alternative, nuclear, the properties of which can be generalised to similar facilities such as hydro. A company is considering to invest in one facility, in the presence of uncertainties regarding the carbon and electricity prices. The investment decision can be taken immediately or be postponed to obtain more information regarding the expected future carbon and electricity prices. Once the decision to invest is made, it is followed by a construction period, which after the plant can be taken into operation. In later time states, a company can also make a decision to retrofit carbon capture and storage (CCS) to coal or gas facilities, if the cost of carbon allowances become high enough.

Apart from deciding upon the timing of the investments, the company considers how the investments are to be financed. The investments can initially be financed by using full, part, or no debt capital depending on the asset circumstances of the company (see Figure 1). Later on the company may decide to pay off some of its debt until finally the remaining debt is paid off at the end of the life time of the plant. The company's cash position is hence dynamic and depends on the revenues received, taxes, and debts which are influenced by the depreciation and tax shields.

The risks of the investment are the outcomes which results in lower cash positions than if the investment were not made. We assume that the company's objective is to maximize the expected financial net worth of the investment while acknowledging the credit risks throughout the life time of the power plant.

The investment model therefore consists of the following four modules (i) carbon price scenario generation, (ii) electricity price scenario generation, (iii) investment timing, and (iv) risk analysis. The first module takes as an exogenous input of the expected carbon price trajectory and volatility, and it is assumed that all agents in the model see this underlying scenario for carbon price evolution. The module converts this basic carbon trajectory into temporal carbon prices in discrete intervals from log-normal distributions with a binomial tree sequential dependence. Thus, there is path dependency in the conditional expectations for carbon prices as perspectives move through the scenario tree. The second module takes exogenous assumptions about fuel prices and the electricity generation profit margin to create, with the addition of the carbon prices at the particular points in the scenario tree, wholesale electricity prices. The power prices are assumed to be set by the marginal generator, which could be gas or coal depending upon the additional supplement of carbon at particular points (gas uses about half as much carbon allowance as coal for the same unit of output). The third module formulates the investment timing decision as a stochastic optimisation problem using the carbon and electricity price scenario tree. For a particular technology, the model computes the optimal time to invest, or not at all, under each scenario. Then, the fourth module evaluates the financial risk constraints that are applied for the cash positions. Given the scenario probabilities, and the various financial parameters, the model then allows the computation of the expected net present values, conditional cash-flows-at-risk, and the cumulative probabilities of investment at each of the time intervals, which are the main outputs of the model.

3. The Model Specification

3.1. Carbon Price Scenarios

We represent the uncertain evolution of the carbon price over a finite time horizon $t = 0, ..., T$ using a binomial scenario tree. Each scenario $\mathbf{s^t}$ at time t is a row vector with t elements. The moves in the tree are given by the binary indicator s_i^t which is 1 if the move is up, and

=0 if the move is down in the tree in period $i=1,...,t$ (i.e., all the moves from period 1 until period t). The set of all scenarios at time t is defined as S^t and it consists of 2^t scenarios

$$S^t = \{\mathbf{s^t} | s_i^t \in \{0,1\}, \quad i=1,...,t, t=0,...,T\}.$$

The unique immediate predecessor of scenario $\mathbf{s^t} \in S^t$ $(t>0)$ is $b(\mathbf{s^t}) = \mathbf{s^{t-1}} \in S^{t-1}$ such that scenario $\mathbf{s^{t-1}}$ is the $t-1$ subvector of $\mathbf{s^t}$, also $b^2(\mathbf{s^t}) = b(b(\mathbf{s^t}))$ and so on.

We define

$F^{-1}(u):\ [0,1] \to \mathbb{R}$ inverse cumulative log-normal probability distribution for carbon prices,
$g_{bin}(i,t,0.5):\ [0,1] \to \mathbb{R}$ binomial probability distribution $i=0,...,t$,
$\mu_t \in \mathbb{R}^+$ the expected carbon values at time states $t=0,...,T$,
$c^e_{\mathbf{s^t}} \in \mathbb{R}^+$ cost of an emission contract to emit one ton of CO_2, $\mathbf{s^t} \in S^t$,
$prob_{\mathbf{s^t}}$ $\in$ [0,1] probability of occurrence of scenario $\mathbf{s^t} \in S^t$, and
q_t $\in$ [0,1] probability of move up in scenario tree at time state $t=0,...,T-1$.

The recombining carbon price scenarios are generated from inverse log-normal cumulative probability distribution $F^{-1}(u)$ where points $u \in [0,1]$ are the mid points of the probability masses of binomial distribution $f_{bin}(i,t,0.5)$, $i=0,...,t$ (cf. Figure 2). The probabilities of moving up at time states $t=0,...,T$ in the scenario tree are solved recursively matching the expected carbon prices μ_t

$$\sum_{\mathbf{s^t} \in S^t} prob_{\mathbf{s^t}} c^e_{\mathbf{s^t}} = \mu_t \tag{1}$$

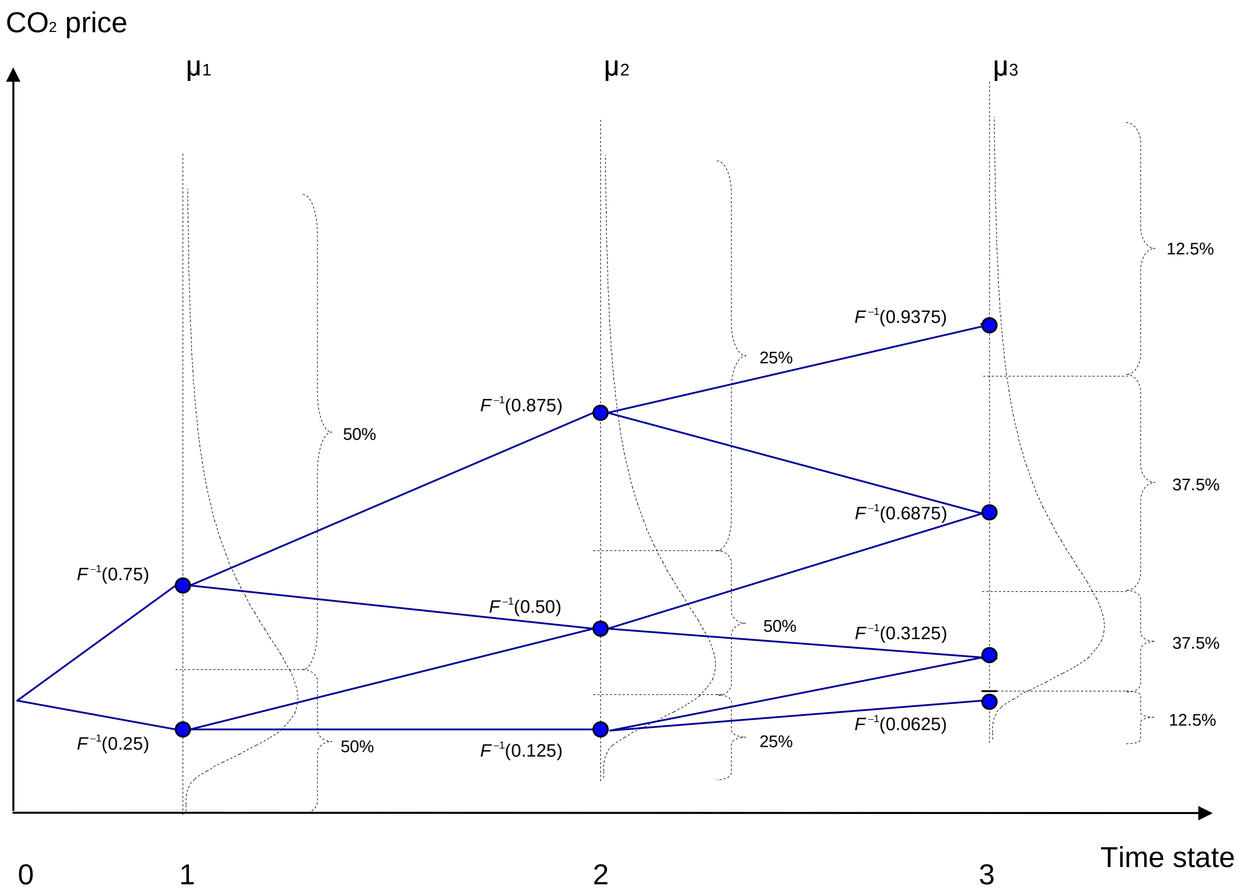
$$prob_{\mathbf{s^t}} = \prod_{j=1}^{t} q_j^{s_j^t} (1-q_j)^{1-s_j^t}. \tag{2}$$

3.2. Electricity Price Scenarios

We introduce the following notation to derive the electricity prices:

$I = \{g, c\}$ set of price setting plants (g=CCGT, c=coal),
$p_{\mathbf{s^t}} \in \mathbb{R}^+$ electricity price/MWh, $\mathbf{s^t} \in S^t$,
$y \in \mathbb{R}^+$ spread on electricity price/MWh,
$e^i \in \mathbb{R}^+, i \in I$ tons of CO_2 emission/MWh, and
$c^{vi} \in \mathbb{R}^+, i \in I$ variable cost of power plant/MWh capacity.

Figure 2 **An example of CO_2 price scenario generation from log-normal distribution**



The electricity price is, $\mathbf{s^t} \in S^t \; t = 1, ..., T$

$$p_{\mathbf{s^t}} = y + \max_{i \in I} \left[c^e_{\mathbf{s^t}} e^i + c^{vi} \right]. \tag{3}$$

It is based on a simple stack model in which the marginal cost producer is either coal or the CCGT plant depending on the cost of the emission contracts.

3.3. Investment Model

The decision variables are (suppressing, for clarity, the superscript i for technology type):

$x_{\mathbf{s^t}} \in \{0, 1\}$ decision to build power plant at time state t, $\mathbf{s^t} \in S^t$,
$x^o_{\mathbf{s^t}} \in \{0, 1\}$ decision to build CCS facility at time state t, $\mathbf{s^t} \in S^t$, and
$x^d_{\mathbf{s^t}} \in \mathbb{R}^+$ decision to pay the specified amount debt back at time state t, $\mathbf{s^t} \in S^t$.

Within the investment optimisation model, we define the following (again suppressing the superscript i for technology type):

Δ time in years between time states $t = 0, ..., T$,

$v_{\mathbf{s^t}} \in \mathbb{R}^+$ annual revenue from power generation, $\mathbf{s^t} \in S^t$,

$j \in \mathbb{Z}^+$ construction time of a power plant in number of time states $t = 0, ..., T$,

$c^f \in \mathbb{R}^+$ yearly fixed operating cost of power plant,

$u \in [0, 1]$ efficiency multiplier of the new plants (compared to the variable costs of pre-existing plant of the same technology in the market),

$c^v \in \mathbb{R}^+$ variable operating cost of power plant/MWh capacity,

$h \in \mathbb{R}^+$ percentage increase in variable cost if CCS built,

$z \in \mathbb{R}^+$ energy production capacity in MWh/year,

$e \in \mathbb{R}^+$ tons of CO_2 emission/MWh of the plant,

$e^o \in \mathbb{R}^+$ reduction in emission in tons of CO_2/MWh when CCS is constructed,

$d_{\mathbf{s^t}} \in \mathbb{R}^+$ one year depreciation of power plant, $\mathbf{s^t} \in S^t$,

$d^o_{\mathbf{s^t}} \in \mathbb{R}^+$ one year depreciation of CCS, $\mathbf{s^t} \in S^t$,

$l \in \mathbb{Z}^+$ lifetime of a power plant in years (including construction time),

$k_{\mathbf{s^t}} \in \mathbb{R}^+$ one year interest payments, $\mathbf{s^t} \in S^t$,

$r^d \in \mathbb{R}^+$ interest rate on debt,

$c \in \mathbb{R}^+$ lump sum investment cost of power plant, and

$c^o \in \mathbb{R}^+$ lump sum investment cost of CCS facility.

The received revenue, interest payment, and depreciation of the investment, we formulate as follows, $\forall \mathbf{s^t} \in S^t$, $t = 1, ..., T$

$$v_{\mathbf{s^t}} = 1_{\mathbb{Z}^+} \left[\sum_{i=1}^{t} (x_{b^i(\mathbf{s^t})}) - j \right] \left[z \left[p_{\mathbf{s^t}} - c^e_{\mathbf{s^t}} (e - x^o_{b(\mathbf{s^t})} e^o) - (1 + x^o_{b(\mathbf{s^t})} h) u c^v \right]^+ - c^f \right] \tag{4}$$

$$k_{\mathbf{s^t}} = \left[x_{b(\mathbf{s^t})} c + x^o_{b(\mathbf{s^t})} c^o - \sum_{i=1}^{t} x^d_{b^i(\mathbf{s^t})} \right] r^d \tag{5}$$

$$d_{\mathbf{s^t}} = x_{b(\mathbf{s^t})} \frac{c}{l} \tag{6}$$

$$d^o_{\mathbf{s^t}} = x^o_{b(\mathbf{s^t})} \frac{c^o}{l - \sum_{i=1}^{t} \left[x_{b^i(\mathbf{s^t})} - x^o_{b^i(\mathbf{s^t})} \right] \Delta} \tag{7}$$

Equation (4) represents the obtained revenues. The multiplication by the indicator function enforces that the revenues are obtained only if the power plant is constructed. Note, that (i) the minimum revenues of the power plant is limited to the fixed operating costs of the power plant as it is not operated if variable operating costs are greater than the obtained revenue from the sale of electricity and (ii) the invested plants are of newer generation than the current ones on operation (which set the market price) and therefore gain the inframarginal profit benefit through the efficiency multiplier u. Equation (5) keeps track of the interest payments on the outstanding principal. Equations (6) and (7) provide the depreciation amount for the power plant and the CCS facility applying a straight-line depreciation method.

We introduce also the following definitions

X^t set of all company's decisions up to time state t,
$a_{\mathbf{s^t}} \in \mathbb{R}^+$ cash position, $\mathbf{s^t} \in S^t$,
$a^0 \in \mathbb{R}^+$ initial amount of available cash,
$r \in \mathbb{R}^+$ opportunity rate of return,
$w \in [0,1]$ company's tax rate, and
$\delta \in [0,...,T]$ final time state when investments can be made.

The overall optimisation problem of a firm is therefore as follows:

$$\max_{X^T} \frac{\sum_{\mathbf{s^T} \in S^T} prob_{\mathbf{s^T}} a_{\mathbf{s^T}}}{(1+r(1-w))^T} - a^0 \tag{8}$$

Subject to cash position constraints, $\forall \mathbf{s^t} \in S^t$

$$a_{\mathbf{s^t}} = \begin{cases} a^0 - x^d_{\mathbf{s^t}} & t=0 \\ a_{b(\mathbf{s^t})}(1+r(1-w))^\Delta - x^d_{\mathbf{s^t}} + & \\ \sum_{i=0}^{\Delta-1} \Big[(v_{\mathbf{s^t}} - k_{\mathbf{s^t}})(1-w) + (d_{\mathbf{s^t}} + d^o_{\mathbf{s^t}})w\Big](1+r(1-w))^i & t>0 \end{cases} \tag{9}$$

decision constraints, $\forall \mathbf{s^t} \in S^t$,

$$x_{\mathbf{s^t}} \geq x_{b(\mathbf{s^t})} \qquad 0<t\leq\delta \tag{10}$$

$$x^o_{\mathbf{s^t}} \geq x^o_{b(\mathbf{s^t})} \qquad 0<t\leq\delta \tag{11}$$

$$x_{\mathbf{s^t}} = x_{b(\mathbf{s^t})} \qquad t>\delta \tag{12}$$

$$x^o_{\mathbf{s^t}} \leq x_{\mathbf{s^t}} \qquad t\geq 0 \tag{13}$$

$$x^d_{\mathbf{s^t}} \leq x_{\mathbf{s^t}} c + x^o_{\mathbf{s^t}} c^o - \sum_{i=1}^{t} x^d_{b^i(\mathbf{s^t})} \qquad t\geq 0 \tag{14}$$

$$0 = x_{\mathbf{s^T}} c + x^o_{\mathbf{s^T}} c^o - \sum_{i=1}^{T} x^d_{b^i(\mathbf{s^t})} \qquad t=T \tag{15}$$

and integrality constraints, $\forall \mathbf{s^t} \in S^t,\ t = 0, ..., T$

$$x_{\mathbf{s^t}},\ x^o_{\mathbf{s^t}} \in \{0, 1\}. \tag{16}$$

Equation (8) maximizes the expected net present value (E[NPV]) of the investment. Equation (9) balances the cash flows, ensuring that the cash position equals cash inflows and outflows during the years between the time states. Equations (10) and (11) enforce that once an investment decision is made it remains. Equation (12) restricts the investment window when the investment can be done. Equation (13) constraints that investment in CCS facility can be taken only if the investment in power plant is done. Finally, equations (14) and (15) restrict that more debt can not be paid back than is initially taken and that it has to be paid back at some point during the investment horizon.

By replacing equation (14) with $x^d_{\mathbf{s^t}} = x_{\mathbf{s^t}} c + x^o_{\mathbf{s^t}} c^o - \sum_{i=1}^{t} x^d_{b^i(\mathbf{s^t})}$ the project can be forced to be **equity financed**. **Project financing** can be forced by adding an additional constraint $x^d_{\mathbf{s^t}} = 0, t < T$. It is straightforward to show with these definitions and the investment equations that if the debt and the opportunity rate of returns are the same, $r^d = r$, the financing structure of the investment does not influence the $E[NPV]$ (consistent with the classic Modigliani and Miller (1958, 1963)). In our stylised framework, however, we envisage the possibility that large incumbent companies have access to lower cost debt than new entrant independent power companies as well as being less risk averse.

3.4. Risk Analysis

To account for the financial risk we use the Conditional Cash Flow at Risk (CCFAR) measure, which is an expected cash flow measure conditional on a particular lower fractile of the cash position. It is defined similarly to the more general Conditional Value at Risk (see eg Rockafeller and Uryasev 2000, Uryasev 2000). We introduce the following additional parameters:

$\alpha\ \in \mathbb{R}^+$ helper variable which equals cash-flow-at-risk when constraint equation (17) is active,
$\beta\ \in [0, 1]$ probability of non-tail event in conditional-cash-flow-at-risk computation,
$\gamma_{\mathbf{s^t}} \in \mathbb{R}^+$ auxiliary variable, and
$\rho \in \mathbb{R}$ risk tolerance measured in conditional-cash-flow-at-risk.

Conditional Cash Flow at Risk (CCFAR) is therefore as follows

$$\rho \le \alpha + \frac{1}{1-\beta} \sum_{\mathbf{s^t} \in S^t} \gamma_{\mathbf{s^t}} \tag{17}$$

$$\gamma_{\mathbf{s^t}} \ge q_{\mathbf{s^t}} (a^0(1+r(1-w))^t - a_{\mathbf{s^t}} - \alpha) \quad \text{and} \quad \gamma_{\mathbf{s^t}} \ge 0. \tag{18}$$

These risk constraints can be set for multiple points in time concurrently to manage the risks through out the power plant's life time. This is important as investments in power plants are long-lasting and risk management applied only at the terminal period would overlook the risk of financial distress during the plant's life time.

Using the risk constraints we can define **a Risk neutral investor** as a decision maker which maximizes return in $E[NPV]$ and **a Risk averse investor** as a decision maker which minimizes the risk exposure, in CCFAR. This is done by supplementing the objective function equation (8) with the CCFAR risk objective $-\lambda\rho$ where the risk aversion factor $\lambda \to 0^+$ if the function characterizes risk neutral investor and $\lambda \to \infty$ if it characterizes a risk averse investor.

4. Computational Experiments

The experiments were done with an evaluation horizon consisting of $t = 0, ..., 6$ time states, such that investment in a power plant was possible in time states $t = 0, ..., 4$ and for CCS in $t = 4$. Each of the first 4 time periods were 3 years. Periods 5 and 6 varied by technology in order to incorporate the full operating life in the case where the investment is made at the end of period 4. Recall that the focus of this work is not to compare the economic value of different technologies, as in conventional long term capacity planning models, where considerable care has to be taken to evaluate alternatives over the same economic horizons, but rather we are seeking to test the propensity to invest in a particular technology against various behavioural and policy assumptions. In a liberalised market with heterogeneous agents, it is perhaps more relevant for Governments to understand the effectiveness of investment incentives upon particular players with their own strategic inclinations, than to envisage an optimal long-term, least-cost market planning solution. We evaluated CCFAR risk constraints on time states $t = 5, 6$ which are the mid and terminal states of the investment, for the cash flow 5% percentiles ie, $\beta = 0.95$. We did not consider risk constraints in the very beginning, since during the construction and the early periods of operation, investors would still be taking a

Table 1 Data for the experiments

Common parameters		Values		
μ_t	expected carbon prices for period 0,...,4 (£/tons of CO_2)	17, 21, 24, 27, 30		
r	opportunity rate of return or return on excess cash (%)	12		
r^d	interest rate on debt (%)	12		
w	tax rate (%)	38		
y	profit spread of electricity price over the marginal production cost (£/MWh)	5		
$\Delta_1, ..., \Delta_4$	length of time periods 1,2,3,4 (years)	3		
z	effective yearly electricity production capacity (TWh)	7.5		
Power plant dependent parameters		**CCGT**	**Coal**	**Nuclear**
j	construction time (years)	3	3	6
l	life time (years)	30	40	50
Δ_5, Δ_6	length of time periods 5 and 6 (years)	16, 17	21, 22	28, 28
μ_t	expected carbon prices for periods 5 and 6 (£)	39, 49	41, 53	45, 60
c	lump sum investment cost of power plant (millions of £)	300	600	1500
c^o	lump sum investment cost of CCS facility (millions of £)	200	400	-
c^f	fixed operating cost (millions of £/ year)	16	24	36
c^v	variable operating cost (£/ MWh)	25	12	3
u	efficiency multiplier of new plant (%)	90	85	100
h	increase in variable cost if CCS facility built (%)	50	75	-
e	CO_2 emissions (tons/MWh)	0.35	0.75	0
e^o	CO_2 emission reductions of CCS (tons/MWh)	0.3	0.65	-

Data is estimated from a number of sources, such as Metz et al. (2005), Blyth et al. (2007), and various industry experts. Note that the construction times assume that all preliminaries are done, such as general permission and licensing, construction plans, grid connection agreements, etc...

longer term view on the project. The base case assumptions are represented in Table 1. The formulation presented in equation 4 was linearized and the equation 9 was adjusted for the different lengths between the time states. The binomial carbon price scenarios were created from log-normal distributions expected values as listed in Table 1, and volatilities of 20%.

4.1. Specification Relevance

Since an important aspect of our investment model is the incorporation of uncertainties, real options, and financial details (i.e., depreciation, tax, and debt financing), an initial set of experiments were undertaken to calibrate the relevance of these features against a simple, purely economic, net present value evaluation. Table 2 summarises this comparison using the base case data. Remarkably, it highlights that all of the power plant investments would be dismissed based on a simple NPV or return on capital expenditure (ROCE) analysis, yet

Table 2 Comparison of different investment models (NPV in million £)

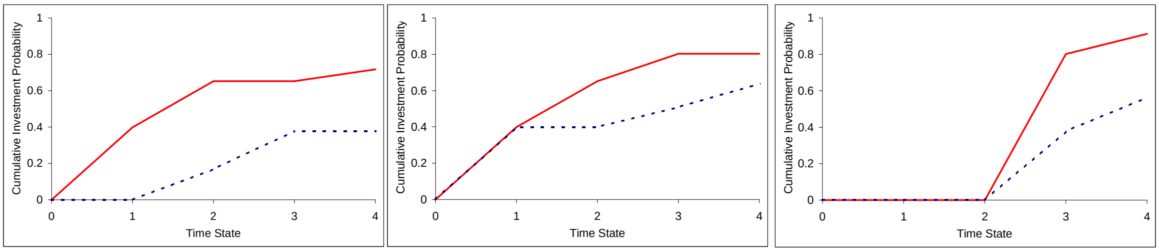
	Nuclear		Coal		CCGT	
	NPV	ROCE	NPV	ROCE	NPV	ROCE
Conventional	-304	-20%	-168	-24%	-66	-19%
Uncertainty included	-245	-16%	-84	-12%	20	6%
Uncertainty and real options included	91	38%	123	73%	120	102%
Uncertainty, real options, and financial details included	349	54%	249	91%	197	131%

they are all highly profitable when the three behavioural elements are included. The simple NPV assumes that the investment is made and paid for immediately, and that subsequent earning are discounted pre tax. For example, the NPV and ROCE of the nuclear power plant investment change from -£304 million and -20% to £349 million and 54% respectively. Including carbon price uncertainty increases plant's value as in the low carbon and electricity price scenarios losses are reduced by not operating the power plant. Consequently, the maximum loss is limited to the fixed operating costs of the plant (see equation 4). The value of the investment increases further when real options to postpone the investment decisions and also the financial planning details are included. The incremental effect of including financial planning details is strong as it increased, for example, the NPV of the nuclear power plant by £258 million and ROCE by 16%. This difference comes from the effective use of the depreciation and interest tax shields.

Figure 3 shows the investment timing and cumulative investment probabilities (ie, $\sum_{\mathbf{s^t} \in S^t} prob_{\mathbf{s^t}} x_{\mathbf{s^t}}$ at time t) with and without financial details. As might be expected, the impacts are greater on the more capital intensive projects, nuclear, then coal, then gas. The effect are substantial and so any capacity modelling without considering the financial planing details would underestimate the propensity to invest in the capital intensive projects, and furthermore, suggest that selective taxation and depreciation incentives for these technologies could have material benefits, if policy were so disposed.

It is surprising that including financial details makes such a big difference in the profitability. Earlier work by Bunn et al. (1993) suggested that financial details are second order effects, but that analysis did not incorporate all of the three elements at the same time, nor did it focus more precisely upon the propensity to invest. Thus, it seems that all of the three behavioural specification elements beyond simple economic NPV are important to include simultaneously in more precise investment modelling.

Figure 3 **Investment decision in (a) nuclear, (b) CCGT, and (c) coal power plants with financial details (solid line) and without financial details (dashed line)**



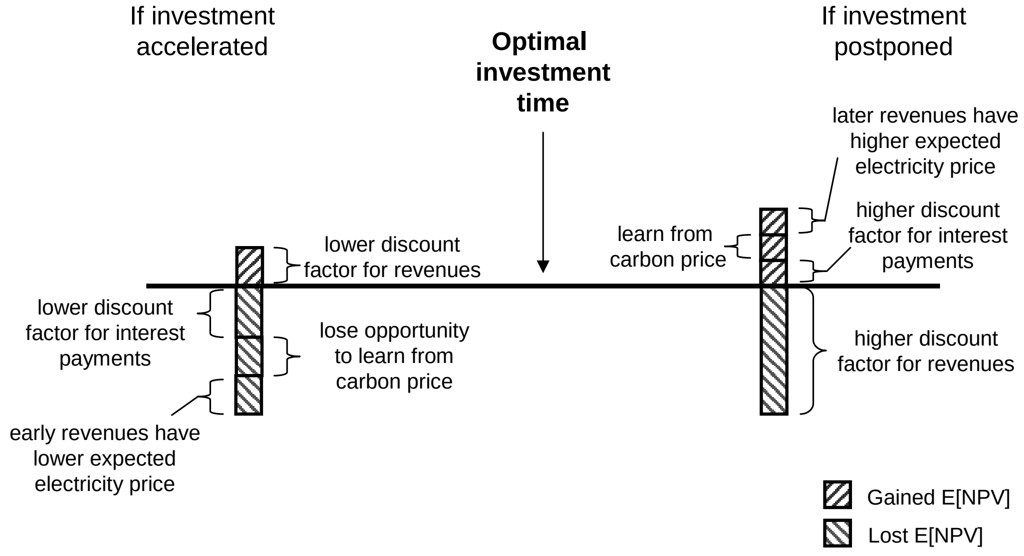
(a) (b) (c)

4.2. Economic Policy

The economic policy experimental variations were done from the perspectives of risk neutral and risk averse investors (eg large and small players respectively). We analyze the effects of the economic policies in terms of encouraging (discouraging) investments, i.e. whether the cumulative investment probabilities are higher (lower) and the "gap" in these probabilities between the risk neutral and risk averse market participants. We propose the following hypotheses:

- H1: Enforcing a floor or cap on the carbon price decreases the gap between the investment probability of the risk neutral and risk averse investors as the volatility in electricity and carbon prices is reduced. (The desirability of closing the gap between the risk averse and risk neutral players could be motivated by policy aspirations to encourage new entrants into the market.)
- H2: Enforcing a floor (cap) on the carbon price encourages (discourages) investments in inframarginal technologies as expected revenues are increased (decreased) because of the pass through of carbon into electricity prices. (Capital intensive investors, eg nuclear, may argue that they need a guaranteed level of policy support in order to proceed.)
- H3: Whilst retaining the overall unconditional carbon price expectation, if Governments introduce major carbon policy changes, or shocks, in early time periods, these will discourage the investments of risk averse investors, as risks in terms of volatility are increased, but encourage the investments of risk neutral investors as early shocks provide more information regarding the conditional expectations of the carbon price evolution. (This hypothesis is the converse of a belief, often expressed in industry, that Governments should maintain carbon price stability by holding back potential market shocks in the social cost of carbon for longer periods than their emergence would imply.)

Figure 4 **Investment timing**

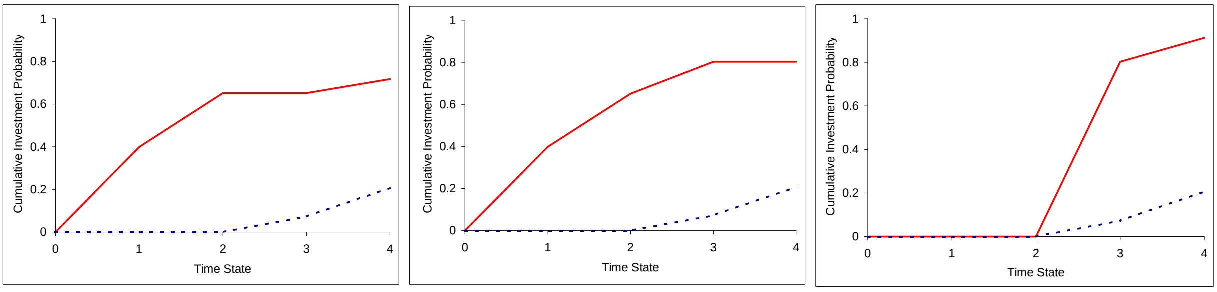


- H4: Providing free CO_2 emission allowances during the early periods for new power plants encourages investments as it increases revenues. (This was the motivation in Phase 1 of the EU carbon trading, although it does open up the criticism of providing excessive windfall profits to those who emit most carbon dioxide.)

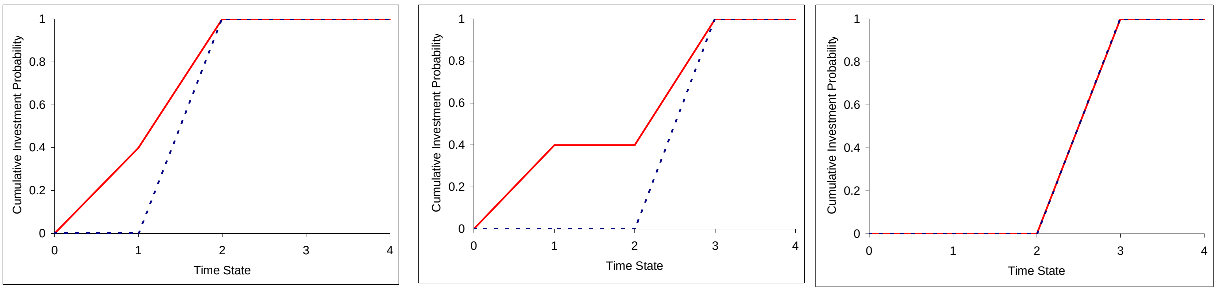
The base case, in Figure 5 (a), illustrates that the risk averse investor postpones the investment decision in all technologies as it can thus (i) learn more information regarding the expected carbon price and then invest selectively in cases where risks are the smallest and (ii) have the CCS technology available at $t = 4$. The risk neutral investor does not invest moreover at t=0, as it balances between the benefits of investing early to earn revenues and of postponing to (i) learn and eliminate investments in the unprofitable scenarios, (ii) receive higher revenues on later time periods as the carbon and electricity prices are expected to be higher in the future, and (iii) discount the interest payments more heavily (see Figure 4).

From the base case we can observe that risk averse investors' investment propensities are actually the same for all technologies, since the risk averse investments are only done in the same high carbon and electricity price scenarios when the downside risks are the smallest. More significantly the risk averse propensities are all very low and substantially below the risk neutral. Investment is much more likely, therefore, in any technology, by the risk neutral incumbents. With coal, moreover, both risk averse and risk neutral investors prefer to wait for the availability of the CCS technology.

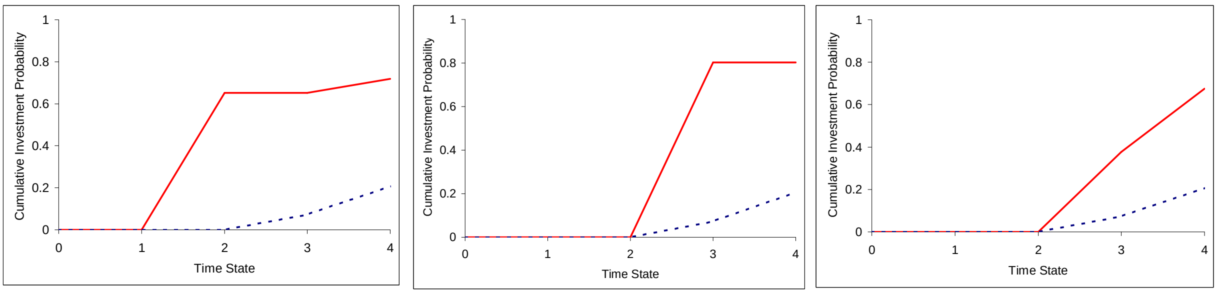
Figure 5 **Investment decision (a) in base case, (b) when a floor (on the level of expected carbon price of the time state) is applied, (c) when a cap (on the level of the expected carbon price of the time state) is applied, and (d) when major policy changes, or shocks, at $t = 2, 4$ are included. The graphs from left to right are for nuclear, CCGT, and coal power plants where solid line is risk neutral and dashed line risk averse decision maker**



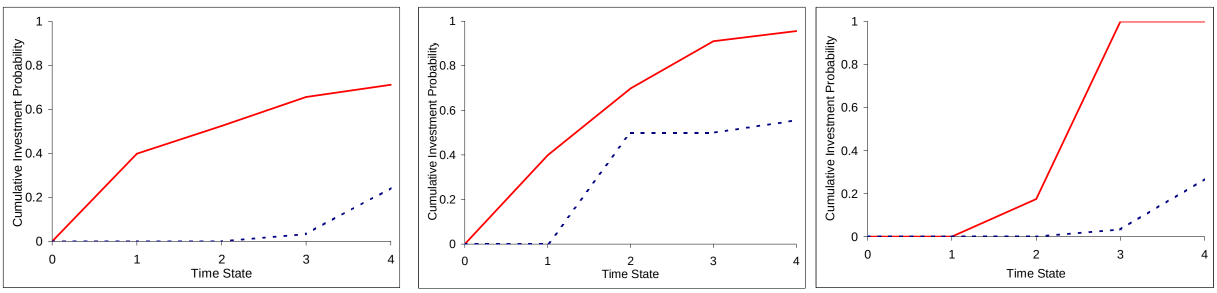
(a)



(b)



(c)



(d)

The effects of floors and caps is demonstrated in Figures 5 (b) and (c) (for summary of the indications on all of the hypothesis see Table 3). With a floor imposed on the carbon price, the propensity of the risk averse participant to invest increases substantially, and significantly closes the gap with the risk neutral investor. This is very apparent for the more capital intensive plant. For coal, risk aversion does not make any difference, and for nuclear, there is only an apparent delay in the first three years. This removal of the corporate discrimination in investment may be more interesting for policy than the overall increased propensity to invest. In contrast, the opposite effects of the cap are most evident for the risk neutral coal investor whose investment probabilities are reduced. However, the cap did not seem to postpone the investment decisions of the risk averse investors.

To test the effects of having major policy changes in earlier periods, we included large shocks up or down in the expected carbon price at time states t=2 and t=4. These shocks were modeled symmetrically, such that the probability to jump up and down was 50% and the jump sizes were 50% of the expected carbon price at t=2 (i.e., £13.5/tons of CO_2). Hence, the expected carbon prices at all time states remained the same as in the base case but the volatility was increased.

As Figure 5 (d) shows the hypothesis 3 regarding the shocks is partially refuted. The increase in volatility encourages risk neutral investments. The reason is that the shocks occur during the early periods when the investor can learn from them and make more profitable investments. This is particularly the case in the CCGT and coal power plant investments as investors have better knowledge whether to build the CCS facility. The early shocks increased the $E[NPV]$ of risk neutral investor by 12%, 23%, and 36% for nuclear, coal, and CCGT plants respectively. It also substantially increased the propensity for the risk averse investor in CCGT. This seems to suggest, that it is not in the interests of Governments to "hold back" carbon price shocks from the trading mechanism, if they are beginning to emerge in the scientific awareness and geopolitical processes of global climate change mitigation.

The "free allowances" hypothesis 4 was confirmed in an experiment in which emission contracts equivalent of the emissions of a CCGT plant were provided for free during the first 4 time states if a power plant was built. This was an effective instrument to encourage risk neutral investors as all of the investments would be made at t=0 with 100% investment probability. This policy had similar effects on the risk averse investor's CCGT investment, but no significant effects on coal or nuclear power plant investments as the acquired windfall profits are smaller fractions of the capital costs and as these plants last 10 to 20 years longer, during which time the same risks exist as without this policy.

4.3. Behavioural Differentiation

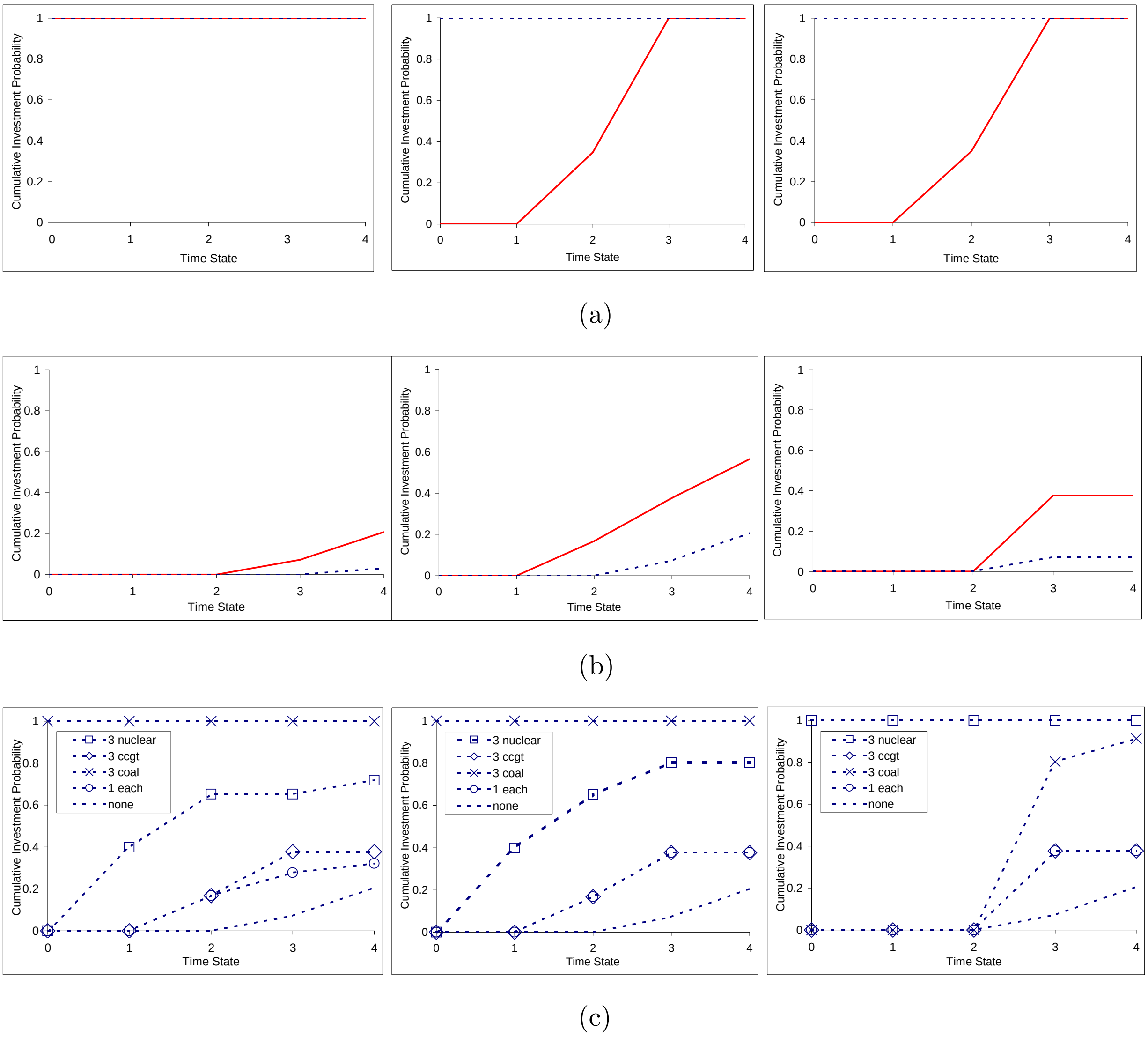
To get an understanding of the economic effects of the carbon policy, it is necessary to investigate the behavioural differentiation of different types of companies. We analyze how different financial situations, the availability of alternative opportunities, and an existing portfolio of power plants affect the propensity to invest. We propose the following hypotheses:

- H5: Higher (lower) opportunity rate of return discourages (encourages) investments as the hurdle rate to invest is higher (lower).
- H6: Higher (lower) debt rate discourages (encourages) investments as the investments become less (more) profitable.
- H7: An existing portfolio encourages the investments of a risk averse investor as the investment can be used to hedge risks.

In the investigation of the financial differentiation of the companies, we relax the assumption of having perfectly efficient capitalisation and financing, where $r^d = r$. We consider that a financially stronger company may be able to borrow money with a lower debt rate than another even though the opportunity rate of return may still be the same for both. By varying the debt rate and the opportunity rate of return it is possible to characterize a financially stronger and highly capitalized or a financially weaker and strongly leveraged player.

Figure 6 (a) is consistent with the hypothesis 5 in terms of increased investment probabilities following from a lower cost of capital. It also demonstrates that risk averse investor may invest before the risk neutral investor in the CCGT and coal power plants. This is because risk neutral investor is willing to take more risk in the tradeoff of a higher E[NPV] as the future carbon and electricity prices are expected to be higher. Note, also that as $r = 5\% < r^d = 12\%$, the financing of the project is optimal using equity rather than debt. If $r = 5\%$ and equity financing is not available and the maximum amount of redeemable debt is limited to the cash proceedings of the investment, the investments of both investors are encouraged but the effects are not as strong as if full equity financing is available. Experiments with $r = 20\%$ confirmed partially the hypothesis 5. The investments of the risk neutral investor

Figure 6 **Investment decision when company has (a) a lower opportunity rate of return $r = 0.05$ and (b) a higher debt rate $r^d = 0.2$, and (c) an existing portfolio of powerplants. The graphs from left to right are for nuclear, CCGT, and coal power plants where solid line is risk neutral and dashed line risk averse decision maker**



were discouraged as expected, but the investment propensities of the risk averse investor remained the same as in the base case.

Clearly, higher debt rate discourages investments, as suggested by hypothesis 6, as Figure 6 (b)shows a financially troubled company, $r^d = 20\%$, where investment was not permitted to be equity financed and the maximum amount of redeemable debt was limited to the cash proceedings of the investment. If equity financing were possible and $r^d = 20\%$ the investments would be fully equity financed and identical to the base case. Lower debt rate, $r^d = 5\%$, confirmed hypothesis 6.

Hypothesis 7 was tested by examining how the investment behaviour of the risk averse incumbent investor differs from a new independent power producer. The existing portfolio consisted either of 3 nuclear power plants, 3 coal power plants, 3 CCGT power plants, or 1 power plant of each type. As Figure 6 (c) illustrates, hypothesis 7 holds. This suggests that the optimal portfolio selection of the risk averse investor will depend on the pre-existing plants. It also indicates that the emergent portfolios are likely to be more diversified than, for example, in Roques et al. (2008) where pre existing portfolios were not considered and single technology portfolios were found to be optimal in several cases.

In particular, Figure 6 (c) shows that the earliest investment in nuclear power plant at $t = 0$ is encouraged if the existing portfolio consists of coal power plants and vice versa. The explanation is that nuclear and coal power plants are a mutual hedge. In low carbon price scenarios coal power plant is the more profitable while in high carbon price scenarios it is the nuclear power plant. If an investment is considered for a CCGT power plant then an existing portfolio of coal power plants encourages the earliest investment at $t = 0$. This occurs as coal and CCGT plants can benefit from the fuel switching. In low carbon price scenarios CCGT plants are the marginal cost producers and in high carbon price it is the coal plants. The reduction in the portfolio risks due to these diversifications are 9%, 6%, and 33% when investments are made for nuclear, coal, and CCGT plants respectively. What is particulary interesting here is that the diversification strategies appear to be quite selective, and mainly relate to coal and nuclear interactions. A pre-existing, fully diversified portfolio of three different plants is not substantially advantageous, compared to none, for any investment, nor is a portfolio of three CCGT plants. This suggests an interesting path dependency in the evolution of market structure according to pre-existing asset bases, and that complete diversity may not be a simple answer to risk management. We also experimented with the changes in investment strategies of the risk neutral investor in the presence of an existing portfolio. As expected, without any risk aversion, the portfolio benefits were immaterial.

The behavioural differentiation of the companies in the market may also stem from the different structural aspects related to the (i) profitability of the electricity generating sector, (ii) adoption rate of the CCS technology, and (iii) availability of the CCS technology. We provide the following hypotheses:

- H8: Harsher (More relaxed) electricity price competition discourages (encourages) investments as the revenues are reduced (increased).

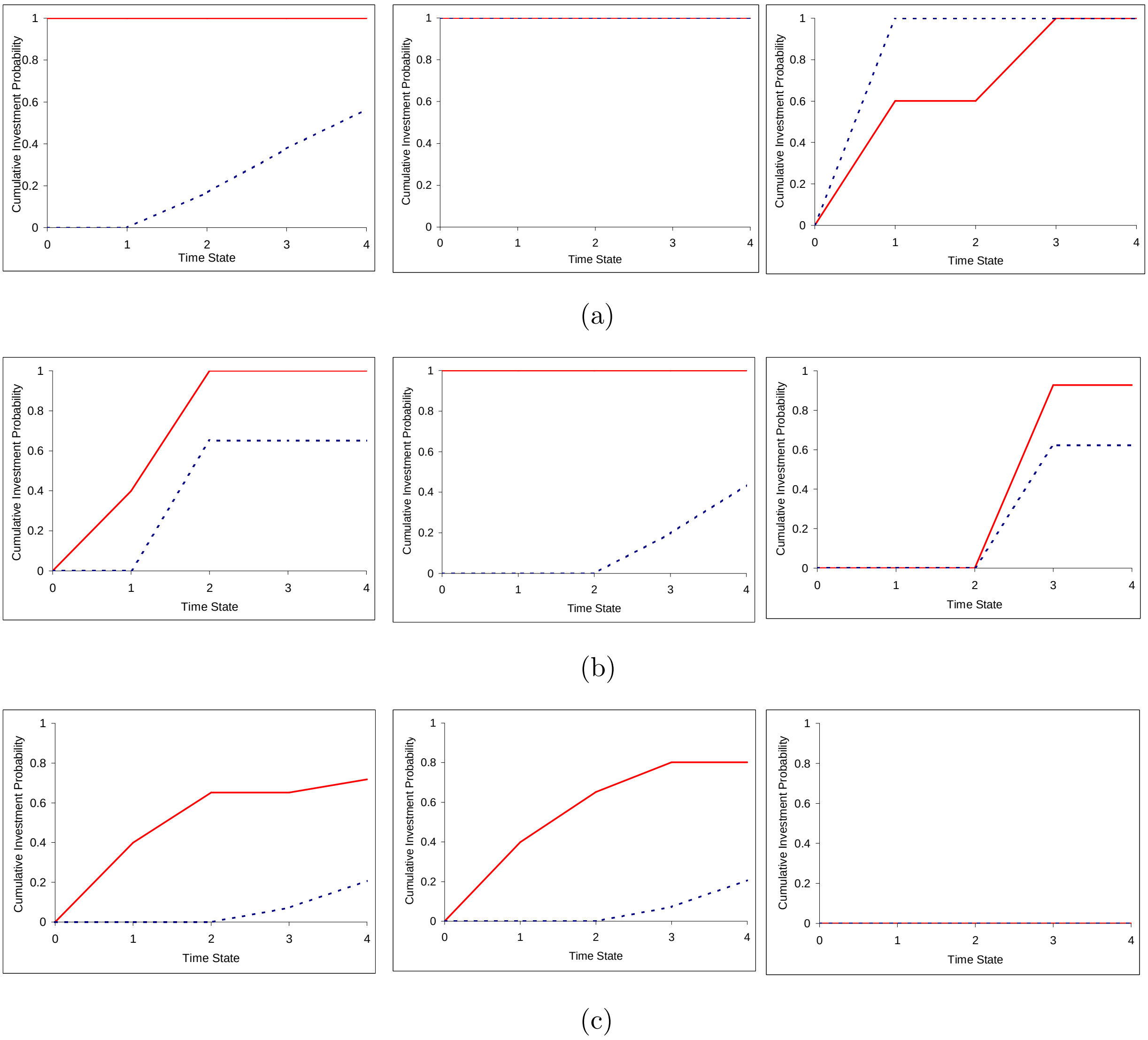
- H9: Faster CCS technology adoption rate discourages investments as the revenues are reduced due to lower carbon and electricity prices.
- H10: Faster CCS technology adoption rate decreases spread between the investment probability of the risk neutral and risk averse investors as the volatility of the electricity is reduced.
- H11: Lack (Availability) of the CCS technology discourages (encourages) CCGT and coal power plant investments as CCS cannot be used to hedge against high carbon price scenarios.

The effects of lower competition in the electricity sector leading to a higher profit margin of $y = £10/MWh$ confirmed Hypothesis 8 (see Figure 7 (a)). Surprisingly we see that a risk averse investor invests earlier in coal power plant than the risk neutral investor. This occurs because the cost of waiting is evidently higher and the risk averse player is less willing to trade that off against the expected value of waiting. We experimented also with narrower profit margin spreads and the results were consistent with hypothesis 8.

Faster adoption of the CCS technology was tested by including the CCS facility in the marginal production cost plants at time state $t = 5, 6$ (i.e., in the equation 3). This decreased the electricity prices at high carbon price scenarios due to the reduction in the emissions e^o but increased the electricity prices at low carbon price scenarios with the additional variable costs of the CCS facility h. These effects are asymmetric and the reductions outweigh the increases, reducing the expected electricity prices. As a result, the $E[NPV]$ of the risk neutral investors were reduced by 25%, 30%, and 40% for nuclear, coal, and CCGT power plants respectively. Surprisingly, all the investments are encouraged and the hypothesis 9 refuted (see Figure 7 (b)). The explanation for the increase in the investment probability is that the reduction in the volatility of the electricity price allows investors to make better investment decisions. Note, also that the investment strategies of the risk averse and risk neutral investors are closer to each other, in the coal and nuclear cases, due to the reduced volatility, hence confirming hypothesis 10.

As suggested by hypothesis 11, investment in the coal power plant without an opportunity to retrofit the CCS facility is discouraged and investment probability is reduced to 0% (see Figure 7 (c)). The investment probability of the CCGT power plant, on the other hand, is not affected though the E[NPV] is reduced, eg risk neutral investor loses 25% of its E[NPV].

Figure 7 **Investment decision when company expects (a) the price competition to be more relaxed $y =$£10, (b) the CCS technology adoption rate to be faster, and (c) the retrofitting of the CCS facility to be impossible. The graphs from left to right are for nuclear, CCGT, and coal power plants where solid line is risk neutral and dashed line risk averse decision maker**



The reason is that in the higher carbon price scenarios, in which CCS would have been built, existing coal power plants are the marginal cost producers resulting in profits for the CCGT plants regardless of the availability of the CCS technology. Hence, the CCS facility is not as crucial for the CCGT plants in short term as it is for the coal power plants. However, the lack of the CCS technology could eventually force coal power plants out of operation which after CCGT plants would be the marginal cost plants and their profitability would obviously then be eroded.

Table 3 Summary of the hypotheses validity

Hypotheses	Validity
H1: Floor and cap decrease the spread between the investment probability of the risk neutral and risk averse investors	Confirmed
H2: Floor (cap) encourages (discourages) investments in inframarginal technologies	Partially confirmed
H3: Early carbon policy shocks discourage (encourage) the investments of a risk averse investor (risk neutral)	Partially refuted
H4: Providing free emission allowances for new plants encourages investments	Confirmed
H5: Higher (lower) opportunity rate of return discourages (encourages) investments	Partially confirmed
H6: Higher (lower) debt rate discourages (encourages) investments	Confirmed
H7: Portfolio encourages risk averse investments	Confirmed
H8: Harsher (More relaxed) electricity price competition discourages (encourages) investments	Confirmed
H9: Faster CCS technology adoption rate discourages investments	Refuted
H10: Faster CCS technology adoption rate decreases spread between the investment probability of the risk neutral and risk averse investors	Confirmed
H11: Lack (Availability) of CCS technology discourages (encourages) CCGT and coal power plant investments	Partially confirmed

5. Conclusions

Overall, it is evident that including financial details, real options, and uncertainties are crucial in the investment analysis when the capital costs are high and the decisions are irreversible. The more detailed, computational analysis can reveal substantial differences compared to the basic economic net present value evaluation in terms of the value of the investment, the optimal investment timing, and financing structure. Government technology support policies will not, therefore, be properly targeted unless these details are correctly modelled, but they could be very effective. Further, the study demonstrates that pre-existing portfolios are important in the analysis of the risk averse investor in ways that can be quite subtle. Simple broad diversity may not necessarily help, but specific synergies, such as nuclear and coal, can be very effective in promoting investment. Given heterogeneous markets, the effects of government incentives therefore have path dependent aspects depending upon the financial and resource based characteristics of the market participants.

Thus, carbon policy risks have essentially different effects on the investment propensity of companies with different characteristics. For example, larger financially stronger incumbent players are more likely to be less risk averse and have access to lower costs of capital than new, project financed independent power producers. Consequently, their propensites to invest are substantially higher and this will eventually lead into a more concentrated and less competitive market structure. Policies to support floors in the carbon price, the early transmission of carbon shocks to the market and supporting innovation in CCS can all help to reduce this tendency to further concentration, but this is unlikely to be reduced substantially without other anti-trust measures.

The experiments shed light on some surprising aspects. For example, a risk averse investor may, under certain circumstances, invest before a risk neutral investor, even though the overall cumulative investment probability is lower. This can occur, for example, if the market is more profitable for generators. This suggest that in terms of promoting new entrants, allowing the generating business to become more profitable has theoretically attractive, but presumably politically awkward consequences.

Finally, the stochastic optimisation framework with CCFAR constraints provides a useful computational facility for addressing economic policy questions around this important topic. Detail is clearly important and the policy implications subtle. Whilst the model can become much more complicated in its specification, one of the interesting aspects is that within the class of large scale optimisation models for the electricity sector, where there has been enormous research in the past 40 years, the approach taken here deliberately avoids seeking to model the full system of generators in a collective long term optimising way. Rather it focusses upon the effects of incentives on different kinds of players in the market. This seems to be quite relevant in age of liberalised markets, without centralised capacity planning, but it does leave open many aspects of incompleteness, notably strategic inclinations such as first-mover investments, investment signalling, forward contracting, and vertical integration. It also leaves open the endogenous aggregate effects if many agents in the market follow the same incentives. Modelling capacity investment in competitive markets for prescriptive purposes is clearly elusive, as strategic behaviour has many drivers, and in a global context even more. Analysis of a particular market might suggest positive economic investment, but if the agents are mainly international companies, even better opportunities could exist elsewhere. Reflecting upon all of these aspects of corporate investment behaviour, therefore, clearly suggests that modelling in this context has to be very focussed on developing insights into particular issues, and relative propensities, rather than seeking a full system comprehensiveness, despite the increasing capabilities of computational economics.

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