# All Fired-Up about Coal:
# Technology & Policy Recommendations for the 2030 United Kingdom Energy Strategy

by
Kathy A. Donnelly

B.S. Civil Engineering
San Diego State University, 1997

Submitted to the Engineering Systems Division and the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degrees of

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Signature of Author ________________________________________________
Engineering Systems Division and Department of Civil and Environmental Engineering
January 18, 2008

Certified by ________________________________________________
David H. Marks
Morton and Claire Goulder Family Professor
Co-Director, Laboratory for Energy and the Environment
Thesis Supervisor

Certified by ________________________________________________
Stephen Connors
Director, Analysis Group for Regional Electricity Alternatives
Laboratory for Energy and the Environment
Thesis Supervisor

Accepted by________________________________________________
Andrew J. Whittle
Professor of Civil and Environmental Engineering
Chairman, Departmental Committee on Graduate Students

Accepted by ________________________________________________
Dava J. Newman
Professor of Aeronautics and Astronomics and Engineering Systems
Director, Technology and Policy Program

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## ABSTRACT

Given United Kingdom (UK) carbon dioxide emissions policies that direct attention at the electricity segment, the focus is on the largest electricity polluter, coal, and the immediately pressing issue of UK coal policy. There is also some consideration of overall energy systems impacts. Coal is an abundant, yet environmentally damaging fossil fuel at every stage of use. In the European Union (EU), regulation will require Flue Gas Desulphurization (FGD) technology on all existing coal plants by 2016, which represents a large capital expenditure. In addition, the European Union Emissions Trading Scheme will likely require future carbon abatement technologies on coal plants. In fact, several proposed UK coal generators are currently considering uncertain technology solutions to carbon emissions, Carbon Capture and Sequestration (CCS). For these reasons, the future price of coal generation remains largely uncertain with a wide confidence band. This thesis uses real options analysis to develop low, medium, and high coal and carbon prices in the year 2030 to account for future uncertainties. These scenarios are compared against current and proposed coal and carbon policies to determine investment scenario paths, which will allow for investment decision modifications as price and policy factors change.

The major conclusion of the analysis is that when accounting for high carbon and fuel price uncertainties, it is cheaper to build a new supercritical plant than it is to retrofit an existing plant. This is especially true for older plants and if the FGD and CCS technologies will be implemented in stages. Therefore, it is a finding of this thesis that the UK should set stringent coal policy, and support that policy with stringent emissions regulations and planning processes, to send strong price signals immediately to invest today either in new clean coal infrastructure or, preferably, in other sustainable technologies rather than face a costly further delay of energy system investments.

Thesis Supervisor: David H. Marks
Title: Morton and Claire Goulder Family Professor
Director, Laboratory for Energy and the Environment

Thesis Supervisor: Stephen Connors
Title: Director, Analysis Group for Regional Electricity Alternatives
Laboratory for Energy and the Environment

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# CHAPTER 1: INTRODUCTION

The United Kingdom (UK) plans to reduce carbon dioxide emission levels to 60 percent below 1990 levels by 2060 (DTI, 2006c). It's an ambitious goal, and one that the UK is not on the path to achieve without a substantial transition in energy policy to change the way the UK produces and consumes energy (DTI, 2006c). It is a finding of this thesis that existing policies that promote incremental steps will not create this necessary transition. Despite mounting concerns about Global Climate Change (GCC), energy security, and rising fossil-fuel prices, UK energy consumption patterns are not changing significantly (DTI, 2006d). If anything, global and UK consumption will increase as population grows and nations develop higher living standards. Therefore, it is a finding of this thesis that sustainable energy systems should be used to generate energy for increasing UK energy demand. If properly implemented, sustainable energy will reduce $CO_2$ emissions per unit of GDP while preserving or decreasing energy intensity per unit of GDP.

An extensive literature review found numerous existing sustainable energy technologies that would easily compete in a carbon-constrained economy. The UK has an unique opportunity to take advantage of ageing and retiring coal and nuclear power plants to transform the existing electricity generation system into a clean, robust, secure, and diverse system. The overarching question is whether UK energy policy will be strategic and stringent enough to send price signals that will force the UK to make the required transition. With large numbers of political and government actors involved in energy policy, the UK is currently operating under a politically-constrained energy policy (Bower, 2004). This means policymaking will be a slow process. In addition, current energy policies rely heavily on the electricity sector to reduce $CO_2$ emissions (see Figure 3) (ibid). It is a finding of this thesis that UK policy should achieve reductions from every energy sector, and be broad enough to include energy efficiency and demand response policies.

Coal policy is an immediately pressing issue of UK sustainable energy policy. Given the UK tendency to focus emissions policies on the electricity sector, Chapter 4 focused analysis on the largest electricity polluter: coal. Existing coal policies promote incremental steps toward cleaning up coal (JESS, 2006). The problem with this approach is that incremental fixes are expensive and time consuming. It is a finding of this thesis that the UK should push for stringent sustainable energy policy measures now.

Coal is a relatively abundant, yet environmentally damaging fossil fuel at all stages of the life cycle. The European Union (EU) Large Combustion Plant Directive (LCPD) requires desulphurization technology on all coal plants by 2016, or a ramp down to plant closure. Retrofitting existing plants will require a large capital expenditure for the UK (ibid). In addition, the 2005 start of the European Union Emissions Trading Scheme (ETS) assigns a price to and creates a market for carbon. Coal, a heavy carbon polluter, will likely incur heavy costs on the carbon market, since the market should promote cheaper carbon abatement technologies. In fact, several currently proposed UK coal plants are being proposed with future Carbon Capture and Sequestration (CCS) upgrade capability (Marshall, 2006; Milner, 2007).

Due to environmental damage, EU and UK regulations, energy security issues, and price volatilities, the future price of coal generation remains largely uncertain with a large confidence band. To account for uncertainties in design decisions, this thesis employs a real options analysis to define low, medium, and high coal and carbon prices for the year 2030. These scenarios are compared against current and proposed coal and carbon policies to determine investor scenario paths. This approach allows investors and regulators to remain flexible in the design of plants and policies, respectively, as factors change.

Chapter 2 of the thesis presents an overview of carbon dioxide market failures and explains how stringent policies can send strong price signals for current and future investments. The chapter recommends that the UK strengthen best available technology policies to best achievable technologies and to focus on stringent policies. This approach should force innovative and cheaper technology deployment. In addition, the UK should consider a diverse mixture of policies to support sustainable technology innovation and implementation:

- <u>Subsidies</u>—including: (1) banning fossil fuel subsidies and (2) implementing other favorable tax policies. Tax policies should focus on increasing private R&D to advance current knowledge and decrease technology prices, as well as to encourage consumers to install microgeneration and energy efficient measures.

- <u>Direct Regulation</u>—including performance standards, building and production codes, as well as agency enforced prohibitions and injunctions. Direct regulation should focus on pollution prevention and end-use efficiencies.

- <u>Information Programs</u>—increase the availability of consumer information to decrease information asymmetry through educational, real-time pricing, and smart metering programs.

However, these coordinated policy packages will be difficult to create under the current politically-constrained energy policy sector.

Chapter 3 summarizes the UK total energy and electricity use, as well as domestic energy systems. The majority of $CO_2$ emissions are from generating energy as well as consuming it for transport, industrial, electricity, heating, and cooking purposes. After a review of major UK energy policies, it is a finding of Chapter 3 that the disjointed UK energy policy needs to be overseen by one agency with the strength to set and enforce market-wide energy policies in a carbon-constrained economy. This would pull other sectors into the EU ETS, and join all energy-related departments under one management.

In addition, it is a finding of Chapter 3 that the UK's electricity security should be measured according to plant margins, production diversity, and fuel and technology supply, rather than by the current practice of focusing primarily on plant margins. To protect against volatile fossil fuel prices and to control carbon emissions, the best approach is to diversify supply and generation. It is a finding of Chapter 3 that the UK should use domestically available fuel sources like clean coal, wind, hydro, tidal, and solar. The plan should include replacing closing coal and nuclear plants with sustainable generation technologies, such as renewables and clean coal. With upgraded, supercritical coal-burning and carbon capture technologies, the UK can cleanly burn domestic coal supplies. Chapter findings show that renewables should play a strong role in diversification since renewable resource supplies are abundant in the UK and are already competitive with current electricity prices. In addition, the UK should break the heavy reliance on natural gas for electricity and heat generation. As was demonstrated in the winter of 2005/2006 (Figure 8), natural gas prices can sufficiently rise to make coal production cheaper than natural gas (JESS, 2006).

Chapter 4 analyzes clean coal for the electricity generation sector using real options analysis techniques. The goals are to diversify from natural gas and meet $CO_2$ targets. It is a finding of this Chapter 4 that the UK coal system, with dynamic and uncertain future coal and carbon prices, needs a flexible, systems approach to capital investment decision-making. Real options provides decision-makers with a learning tool for more informed strategic decisions since uncertainties are resolved in time through dynamic systems analysis (Mun, 2007). Real options techniques are used to analyze the UK coal system using a binomial lattice process to determine future coal and carbon price probability distribution functions. Next, several scenarios are compared to model possible power plant configurations and the generation capacity of UK coal boilers.

The analysis attempts to address how the UK should dynamically manage their coal system, especially considering the entire energy system, and to what extent to modify existing DTI coal strategies. For instance, to achieve UK $CO_2$ reduction goals and to meet regulations, all coal plants must include Flue Gas Desulfurization (FGD) by 2016 (JESS, 2006). It is a finding of Chapter 4 that near-term conditions will likely require carbon capture and storage (CCS) technology installation; a technology that has not been fully proven yet. When modeled for high carbon and fuel prices—a likely scenario that considers policy and price uncertainties—it is cheaper to build a new supercritical plant than to retrofit an existing plant with FGD and CCS. This is especially true for older plants or if the FGD and CCS are built in stages. It is a recommendation of Chapter 4 that the UK should set stringent $CO_2$ policy across all sectors to send immediate and strong price signals to invest in carbon abatement technology across all sectors now.

Chapter 5 develops conclusions and ties the thesis analysis together to present a better way forward for the UK coal system. The timing is right for immediate policymaker and investor reaction because two-thirds of existing UK coal plants have plans for immediate-term FGD-retrofit. Instead, stringent UK policy would induce these plant owners to invest in supercritical, clean technology now in the most long-term cost-effective manner to achieve future energy policy goals. It would also avoid investments in stand-alone FGD-retrofits, a cost-inefficient way to invest in cleaning up plant emissions, and should encourage these plant owners to invest in other, more sustainable technologies and policies, with the focus on distributed generation renewables and energy efficiency. This means that UK policymakers should support stringent coal policy now to send strong price signals to invest immediately in new clean coal infrastructure and/or other renewable technologies rather than face a costly further delay of energy system investment.

# CHAPTER 2: $CO_2$—A GLOBAL EXTERNALITY

Chapter 2 focuses on Global Climate Change (GCC) externalities due to $CO_2$ emissions, one of the most pressing and complex policy issues affecting the well-being of the economy, the environment, social equity, and humankind. Market and policy failures result from the lack of flexible and stringent policy mechanisms to monitor markets, send price signals, and balance the social costs and social benefits of carbon combustion. Significantly reducing $CO_2$ emissions will require a world-wide systematic approach—considering the global characteristics of pollution, technology diffusion, international trading markets, and global cooperation—to develop a balanced solution. An international approach will be required to correct the market failures that discourage individuals, regions, and nations to abate GHG emissions. This international policy will need support from numerous international and national policies.

The abatement of $CO_2$ emissions is underrepresented in the market due to several factors. Two factors stand out as strong candidates for analysis: information asymmetries and externalities. Traditional economic theory recognizes an externality as a market failure due to unstable property rights of a public good, the atmosphere in this case; however, it also assumes perfect information (with no information asymmetries). In addition, traditional economic theory fails to identify the constant interaction between suppliers and consumers, which results in a static view. On the other hand, a dynamic systems approach to economic theory that considers market (and political and institutional) failures and dynamic growth opportunities would inform policy-makers about ways to send strong price signals.

## 2.1 Two Market Failures: Imperfect Information and Externalities

Imperfect information and externalities directly influence atmospheric carbon dioxide levels, and should be considered in policy-making. Market participants are almost never perfectly informed due to a general lack of information, information asymmetries, and price signaling. For instance, Joseph Stiglitz argues that information inequities are the norm, rather than the exception (Stiglitz, 2002). Information asymmetries also favor industrial interests, like large fossil fuel industries, through influence of political representatives that set legislation. These interests push the environmental clean-up costs onto the public and slow the pace of technology and policy adoption. They also push for things like increased drilling rights and relaxed automobile standards. In fact, the US auto industry has resisted most proposed government requirements, while claiming auto industry economic damage due to inadequately developed technologies. Ironically, the opposite became true: as US automakers have resisted technical change, they continue to struggle in the global market, while the Japanese, European, and Korean automakers have adapted to gain control of the US auto market (Whiteside, 2006).

Information uncertainty is another factor that significantly affects the economic performance of a system. Different types of ignorance make consumers unaware of green products, unable to affect green product availability, oblivious to corporate and government strategies, and unable to receive signals about resource scarcity and price volatility. Imperfect information results in the inability to achieve Pareto efficiency and leads to inadequate information levels and consumer incentives. For instance, in the case of global pollution, consumers are often unaware of pollution emission quantities, energy use, or simple ways to adjust behavior.

Second, consumption of goods and services produces externalities—costs (or benefits) not reflected in the market price that impact a third party with no control over the original market transaction. In a competitive, uncoordinated market, goods with pollution externalities are consumed at inefficient levels, resulting in too much production and consumption (Bjornstad, 2004). Producing and consuming most, if not all, goods (i.e. gasoline, heat, an appliance, clothing, food, solar cells, etc.) produces externalities from $CO_2$ emissions. In the case of $CO_2$, only a small portion of externality costs are currently being paid for by manufacturers and consumers.

Imperfect information and externalities justify government policy intervention to allocate goods and services efficiently. Intense information programs would increase the availability of consumer information, and supporting price-signaling policies would affect consumer and supplier behavior. These programs and policies must be carefully designed to achieve first-best outcomes, and should consider the following GCC causes and effects of imperfect information:

- Scientific evidence of GCC—consumers and politicians are ill-informed of uncertainties or risks associated with GCC, affecting their Willingness to Pay (Demand) for abatement. This is less of a problem in the UK than in many other countries, like the US, China, and India.

- Technology—consumers and (in some cases) suppliers are not adequately informed of availability of abatement related technologies, affecting their product choice.

- Suppliers—suppliers are inadequately informed of the benefits of action (due to poor price signals and supplier uncertainty) versus the costs of inaction (due to imperfect information), and of the demand for cleaner products (affecting their willingness to adapt (Supply))

## 2.2 Existing Policy Mechanisms

Several existing and proposed policies are in place to address pollution, and this section will touch upon effectiveness and/or efficiency factors. One classic response that internalizes $CO_2$ externalities is to tax gas, oil, and carbon to send price signals to users and producers. The objective is to achieve less, and more efficient, consumption as well as long-term behavioral changes. Taxes can potentially return Pareto optimality (Bjornstad, 2004). On the other hand, a government (not private) R&D program to improve technology efficiency, quality, or performance would not send signals to users or producers to change their behavior. Government R&D would thus only achieve a second-best result (Bjornstad, 2004).

Governments often promote energy and environmental policies through classic response subsidies of renewable energy production, insulation installments, energy efficient appliances, as well as hybrid vehicles tax and energy credits. Subsidies can directly impact end-use efficiency through price signals that influence short-term, as well as long-term, behavior changes; and, thus achieve first-best outcomes (Bjornstad, 2004). On the other hand, subsidies can send inefficient information and price signals to consumers, achieving second-best outcomes. For instance, auto subsidies signal the availability of fuel-efficient vehicles, but unlike a tax, fail to signal fuel scarcity or account for pollution externalities, making this a second-best solution that should be used in conjunction with a gasoline tax (Bjornstad, 2003).

Direct regulation, including performance, building, or production standards, codes, prohibitions, and injunctions, may work best when pollution thresholds are close to zero or need strong correction, when monitoring costs are high, and in cases of emergencies; in other words, times when "relationships between costs, values, and damages change abruptly" (Bjornstad, 2004). The weakness is that they fail to achieve the lowest possible abatement costs since each firm is treated identically. For instance, a comparative cost analysis by Tom Tietenberg (1984) found that direct regulation increased costs over market-based policies by two to twenty times (Titenberg, 1984). However, a review of command-and-control (CAC) regulations shows mixed technology-forcing results, including incremental innovation in processes and products, diffusion of existing technology, product reformulation, product substitution, new process development, radical successes, and complete regulation failures. The most influential aspect of direct regulation success is the internal design of the actual regulation, which will be further explored in the next section.

Other types of agreements have been applied to address GCC externalities. For instance, the Clean Development Mechanism (CDM) and the Joint Implementation (JI) programs attempt to increase technology-sharing between developed and developing countries and are designed to promote energy efficiency (Kemfert, 2004). The goal of these mechanisms is to reduce the economic costs of emissions reduction. Although they may be good first steps towards global action, they only provide second-best results under their current design and need further refinement.

Cooperative international climate policy actions have been attempted through the formulation of the Kyoto protocol. The Kyoto protocol, although it may be a step in the right global policy direction, has thus far proved insufficient. The main reason is that the current largest emitter, the US, has not ratified the plan. In addition, developing countries that may be the largest emitters in the future, like China and India, are not required to reduce emissions under the agreement. In essence, a first-best solution has not been developed since many big players are not involved in the agreement. In addition, the Kyoto protocol does not have serious consequences if the participants do not meet goals. To be effective, the Kyoto protocol needs reformulation.

Cap and trade programs attempt to control pollution by setting a limit on emissions and giving allowances to firms which represent rights to emit specific amounts of pollution. Cap and trade programs limit total emissions. In essence, a cap and trade system charges buyers of additional allowances for emissions and the costs of achieving emissions standards remain within the trading market. Optimal emissions levels are calculated to determine the appropriate number of tradable permits. Taxes are another policy tool that can achieve similar reductions in emissions since polluters are induced to reduce emission levels. Quantity instruments (cap and trade systems) and price instruments (taxes) should be more effective depending on whether costs or benefits, respectively, are more uncertain. When properly designed, quantity and price instruments are first-best policy frameworks (Bjornstad, 2004).

Systems like the European Union Emissions Trading Scheme (ETS) can be well-designed to send economic signals to industry to innovate, or improperly designed to result in diffusion of existing technology. If caps are not set stringent enough, the low-cost firms lack incentive to abate additional pollution and the regulation will fail to achieve a socially optimal level of pollution. Past price falls and sluggish futures indicate that the ETS has set stringency standards too low. In addition, allowance credits and caps need to be reduced to achieve optimal pollutant levels.

Chapter 4 will evaluate existing EU and UK coal policy to determine probable future costs of electricity under different policy scenarios. In addition, the European Union Emissions Trading Scheme is further explored in Section 4.3.2 to determine possible impacts on the coal industry.

### 2.3 Forcing Technology

Policy mechanisms to reduce carbon dioxide emissions are limited by design. A good measure of policy success is the degree of resulting technology innovation, which benefits society via positive impacts to economic growth, as well as health, safety, and environmental well-being. US regulators have successfully promulgated industry pollution standards with corresponding achievement targets (e.g. deadlines, technology levels, and effluent quantities) through direct regulation instruments, such as the Clean Air Act. This type of regulation can be designed to “force” industry to reduce pollution by developing and implementing innovative technology. For purposes of this thesis, technology-forcing policy is very important for the growth of sustainable technologies and includes regulation promoting “clean” chemical inputs, process designs and operations, and final products. “Clean” is defined as natural, safe, and low risk chemicals and treatment of chemicals, or pollution prevention; in other words: sustainable technologies. Chapter 4 further explores clean coal technologies.

To understand the dynamic system created by technical innovation, the economic and social benefits of technology forcing can be demonstrated by the following figures. Figure 1 illustrates a static economic system that only considers existing technology. The supply curve, A, equals the marginal cost of pollution reduction, while the demand curve, B, represents the marginal social cost of pollution damage. The willingness to accept dirty air and/or to pay for clean air impacts the demand. This two-dimensional, static system can be used to determine a starting point for carbon dioxide trading prices or taxes (t*). The system is also limited in its application since it is fixed. Outside factors will change as consumer attitudes, technological innovations, and regulations change. If economic analysis is done using these static conditions, it will fail to consider system-wide influences; therefore, a dynamic situation needs exploration.

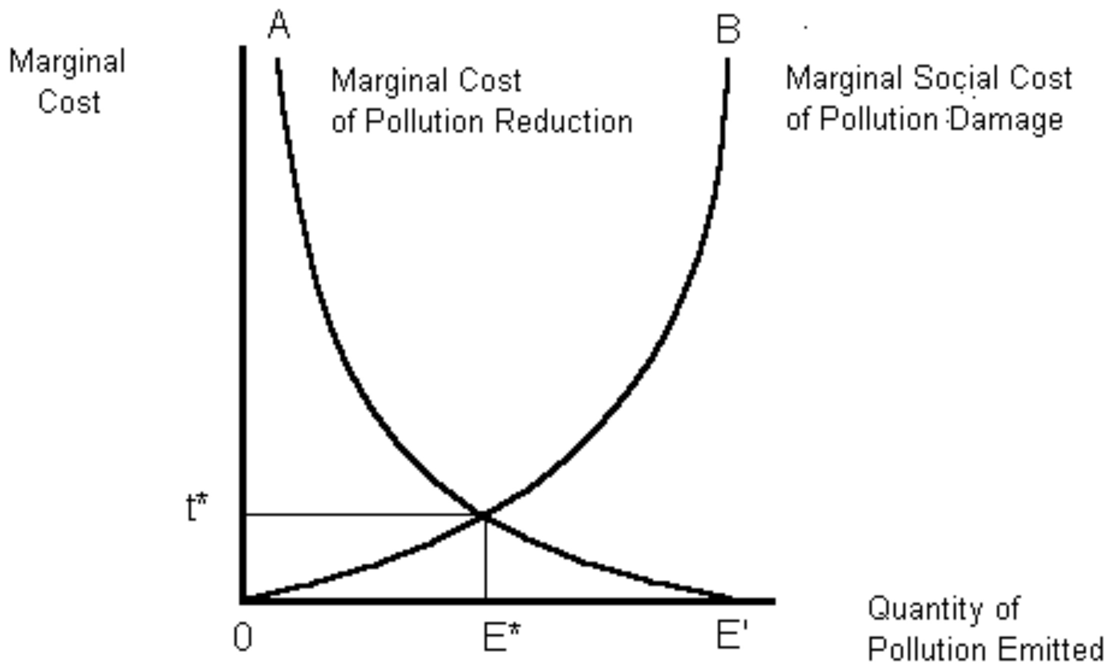



**Figure 1 Socially Optimal Level of Pollution and Cost** (Nicholas Ashford & Charles Caldart, 2007)

On the other hand, Figure 2 represents a dynamic system. It was developed to explain the MIT strong-form of the Porter Hypothesis which concludes that some companies will respond with innovation to create dynamic change (Ashford & Caldart, 2007). This would lead to lower costs and higher benefits. Ashford and Caldart have termed the MIT-Porter Hypothesis, which states that neoclassical economics fails to recognize that different actors, or suppliers, will likely innovate (ibid). Figure 2 includes one demand curve and two supply curves that represent best existing technology and new technology. For the supply curves, at levels of existing technology ($R_0$), the best existing technology is cheaper than new technology. However, as less risk is permitted ($R_1$) and more stringent policy is set, technology innovation can produce cheaper new technology supply curves (see points C and B on Figure 2). Further, for the same cost as existing technology (point B), new technology (point D) can achieve even lower risk levels ($R_2$). Stringent regulation could force the static point (B) to a point on the new technology demand curve between point D and point C. The system should equilibrate at the crossing of the new technology supply curve and the demand for risk reduction benefit curve.

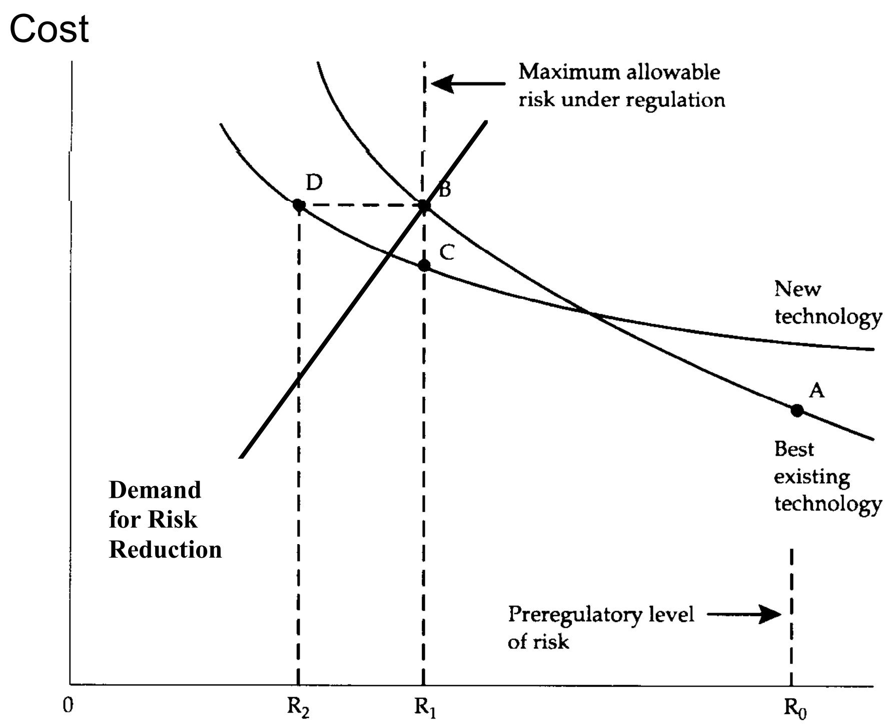



**Figure 2 Dynamic Efficiency of New Technology** (Nicholas Ashford & Charles Caldart, 2007)

This hypothesis finds that stringency is the most important characteristic of effective (i.e. "radical") technology-forcing regulation. For instance, stringent health-based regulations have been more successful at forcing technology than weak technology standards that diffuse, and then freeze, technology development. "Best available" technology standards are an example of a weaker policy that likely does not push industry to innovate. Often best available technology policies induce a slight shift in technology followed by a period of low to no industry innovation, followed by a later slight shift in technology (Nicholas Ashford & Charles Caldart, 2007). On the other hand, best achievable standards mandating currently infeasible or not fully developed technologies coupled with R&D, can force technology innovation, especially when considering high and uncertain fuel and carbon prices. Applying this theory, Carbon Capture and Storage (CCS) technology, which has been successful at one plant in Norway that turns missions into liquid for storage (BBC, 2007), but has not matured enough for full market penetration yet, should benefit greatly from a different strategy of stricter best achievable technology regulation.

In addition, regulators should apply stringent standards not only to new sources, but also to existing plants. Differential regulations result in longer existing plant (dirty) lives, meaning the worst polluters operate longer than they otherwise might have.

Differential regulations can also lead to barriers to entry for new sources by allowing existing plants to operate cheaper.

Current UK regulations require Best Available Techniques Not Entailing Excessive Cost (BATNEEC), following the EU BATNEEC standards (UK, 1990). There is some evidence that Best Available Technology may not push as hard for innovation as more stringent regulation (Nicholas Ashford & Charles Caldart, 2007). It is a finding of this thesis that employing a more stringent best achievable technology, coupled with R&D would produce dynamic efficiency of new technology (Figure 2). BAT technologies can promote incremental changes in technology innovation, but innovation delay from static market conditions can be costly. Stricter standards should stimulate cost-competitive, sustainable technologies through innovation-forcing policies. In fact, stricter standards should induce RD&D for sustainable energy technologies to encourage innovative CCS, new nuclear, renewable technologies, etc.

To test the theory that the result of stringent regulation will be cheaper than less stringent best available technology regulation, Chapter 4 analyzes the $CO_2$ emissions and cost of electricity (COE) impacts of the current EU and UK policies to incrementally ratchet down standards through the LCPD and ETS.

## 2.4 Conclusion

Since imperfect information and market failures eliminate Pareto efficiency, government policy intervention in market allocation of goods and services is justified (Bjornstad, 2004). A policy-influenced market-based type of solution should be implemented to achieve socially optimal and cost-efficient pollution levels. A review of fossil fuel consumption social costs has identified larger macroeconomic impacts from rising fossil fuel prices than benefits from falling oil prices due to externalities not considered by users and suppliers. In other words, a benefits/costs asymmetry (Parry, 2003). Since a global market determines fossil fuel prices, the best methods for protection against price volatility are to diversify energy sources and to reduce fossil fuel intensity (fossil fuel use/GDP). Reducing fossil fuel consumption would also reduce $CO_2$ emissions. The benefits/costs asymmetry enforces the principle that increasing efficiency and usage of sustainable energy, while cutting back on fossil fuel use, should be a primary approach to reducing $CO_2$ emissions. As developing countries like China and India exponentially increase energy use, it is necessary to transition to sustainable, precautionary energy technologies and to create demand-side accountability for levels of use.

A review of UK Department of Trade and Industry (DTI) publications found forward-thinking plans and solutions to several socio-economic problems facing Great Britain and the world, including $CO_2$ pollution. The DTI should continue to support the European carbon market and to lead the world in carbon abatement policy-making. Now the challenge remains to develop first-best policies and market-based instruments that are stringent enough. When properly designed, they send price signals that encourage behavior change—such as buying more efficient vehicles, conserving energy, installing microgeneration, conserving energy, and updating and innovating industry technologies. The price signals create a positive feedback loop that will stimulate technical innovation and further encourage behavior change. Many economists agree that a cap and trade system is more politically palatable, and may be more economically efficient, than a carbon tax. Since direct regulation has proven to be able to achieve technology-forcing, if pollution standards are properly set to compliment market-based instruments, the cap should be low enough to push sustainable technologies and fuels.

Regulation stringency, the most important regulation factor to stimulate technology innovation, should be set to allow industry flexibility and time for R&D to deploy innovative technologies. Flexibility can be achieved through compliance schedules, innovation waivers, and tradable permits systems. Currently, the UK consultation model provides industry and other stakeholders with a chance for input, which should allow for industries to begin early preparation for regulations. However, regulation certainty and stability will increase industry's motivation to accelerate efforts to innovate. Finally, effective monitoring and enforcement should increase policy effectiveness and have positive impacts on technology forcing.

At the focal point of a balanced solution should be a well-designed cap and trade market for carbon. Where appropriate, direct regulation, additional price instruments, subsidies, and information programs should send further signals that would rationally encourage progressive behavior, rather than assuming rational economic behavior to predict actual market behavior. Several policy recommendations are included below:

- <u>Subsidies</u>—including: (1) banning fossil fuel subsidies and (2) implementing favorable tax policies. Tax policies should focus on increasing private R&D to advance current knowledge and decrease technology prices, and to encourage microgeneration installment and energy efficient measures.

- <u>Direct Regulation</u>—including performance standards, building and production codes, as well as agency enforced prohibitions and injunctions. Direct regulation should focus on pollution prevention and end-use efficiencies.

- <u>Information Programs</u>—increase the availability of consumer information to decrease information asymmetry through educational, real-time pricing, and smart metering programs.

Finally, UK regulations requiring Best Available Techniques Not Entailing Excessive Cost (BATNEEC) should be strengthened to stimulate new technology innovation. The BATNEEC standards may not be stringent enough to push dynamic technology innovation, instead encouraging potentially more costly static conditions. If the UK implements stringent regulations and forces technology innovation, the UK should save money on abatement costs and become industry leaders for the resulting innovative technology solutions. Chapter 3 will further explore the UK energy system and develop general policy conclusions and recommendations, while Chapter 4 will test this hypothesis against the UK coal system.

## CHAPTER 3: THE UK ENERGY SYSTEM

UK energy data shows increasing energy consumption across sectors, rising fossil fuel prices, and escalating price volatility. In addition, there is a mounting reliance on natural gas and other fossil fuels for power generation and transport. Depletion of North Sea reserves and the UK's recent move to net importer of natural gas means that—in addition to carbon emissions—energy security issues have become even more pressing. To meet DTI targets of 20 percent renewable electricity generation by 2020, the UK energy system is currently being analyzed by the DTI and industry from all angles. Achievement of these targets will not come easy and will likely result in a geographical redistribution of electricity generating capacity. There are large wind resources in Scotland and in shallow locations off the coast of England and Wales (DTI, 2003b), and microgeneration renewable would generate power at the source. Achievement of UK energy targets will also require investment in additional infrastructure to support electricity transmission, distribution, and exchange among generators and users (DTI, 2003b).

The Stern Review warns that strong action is required immediately to avoid the worst impacts of climate change (Treasury, 2007). It concludes that delay will be more costly than acting now and urges strong, international policy action, including an international emissions trading scheme (ibid). The Stern Review follows the aggressive 2006 Energy Review recommitment to four main goals:

1. Cut $CO_2$ emissions by 60% by about 2050;

2. Maintain reliable supplies;

3. Promote competitive markets in the UK and beyond, raising rate of sustainable economic growth and improving productivity; and

4. Ensure all homes adequately and affordably heated (DTI, 2006c).

Although the analysis section focuses specifically on the coal industry, the overarching thesis question—whether UK energy policy will be strategic and stringent enough to force the UK to make a major transition required to meet Energy Review goals and to heed Stern Review warnings—will be further developed in this chapter.

Chapter 2 examined why UK best existing technology conditions could fail to force technology innovation, while this chapter analyzed the UK energy sector with three major conclusions. First, UK energy and carbon dioxide policy-making is made across numerous different agencies and departments and may be too disjointed to be effective as they could be. An oversight agency with enforcement power should set and oversee UK-wide energy policies to implement a carbon-constrained economy. Second, future DTI UK electricity generation fuel mix estimations show that the UK will remain heavily dependent on natural gas for approximately 75 percent of electricity and space heating needs (DTI, 2006d). To ensure future energy security and a diverse energy system at less volatile prices, the UK should push the development of renewable sources, clean coal industries, and other sustainable technologies. Third, UK policy seems to rely too heavily on the electricity sector to achieve $CO_2$ emission reductions. While looking at all industries in the energy sector is outside the scope of analysis, energy strategies for the coal electricity sector will be explored in Chapter 4.

Chapter 3.0 presents and sums up the UK total and domestic energy system. Chapter 4.0 explores clean coal for the electricity generation sector as a way to diversify from natural gas. Chapter 5.0 uses qualitative and quantitative data to tie the thesis analysis together to present a better way forward for the UK energy system.

## 3.1 Current UK Energy Policy Structure

One of the “big issues” listed by then UK Prime Minister (PM) Tony Blair, climate change, is “probably long-term the single most important issue that we face as a global community” (Maugis, 2006; PM, 2007) . Sustainable policies consider environmental, economic, and equity factors, and energy policy makes up a large part of sustainable policy, especially in the UK. Figure 3 conceptually illustrates England and the UK’s energy policy players considering the related departments that set individual policies related to Energy. Although not depicted, Scotland, Wales, and Ireland also set energy policies. Figure 3 shows that the PM heads the Cabinet Office PM Strategy Unit (PMSU), which is part of the Cabinet Office. Both are directly involved in energy-related policy through the Department of Trade and Industry (DTI) at the core, supported by the Department for Environmental, Food and Rural Affairs (DEFRA), and the Office of Gas and Electricity Markets (Ofgem) (under DTI and FCO influence) (DEFRA, 2007; DTI, 2007b; Ofgem, 2007).

DTI, DEFRA, and OFGEM each play a large role in UK Energy Policy and together they reach across energy-related sectors. The DTI Energy Group, headed by Malcolm Wicks, is charged to provide the UK with safe, secure, sustainable, and affordable energy (DTI, 2007). The DTI led the 2003 and 2006 Energy Reviews with input from the PMSU (DTI, 2003a, 2006c). DEFRA focuses on climate change and energy issues specifically related to sustainable energy and development (DEFRA, 2007). DEFRA allocates UK carbon trading allowances via the UK National Allocation Plan (NAP), which are traded on the European Union (EU) Emissions Trading Scheme (ETS). Ofgem aims to protect UK energy customers, promote competition, and regulate monopolies by regulating gas and electricity markets. (Ofgem, 2007).

As detailed in Figure 3 UK energy policymaking has an expanded field of influence (figure expanded from (Maugis, 2006)). Figure 3 represents several systems related to energy policy, and illustrates the general complexity and overlap in setting energy policy. There are multiple Departments, Cabinets, Committees, and Strategic Units, all under the influence of the Prime Minister of England. There are several connections worth noting. For instance, the Stern Review was conducted under the PM by an independent committee under the request of the Chancellor of Exchequer (Treasury, 2007). The Joint Energy Security of Supply Working Group (JESS) is a collaboration of DTI, Ofgem, the Foreign and Commonwealth Office (FCO), and

National Grid (JESS, 2006). The Energy Saving Trust is funded by the Department for Transport, DEFRA, and DTI with private sector support (EST, 2007; Maugis, 2006).

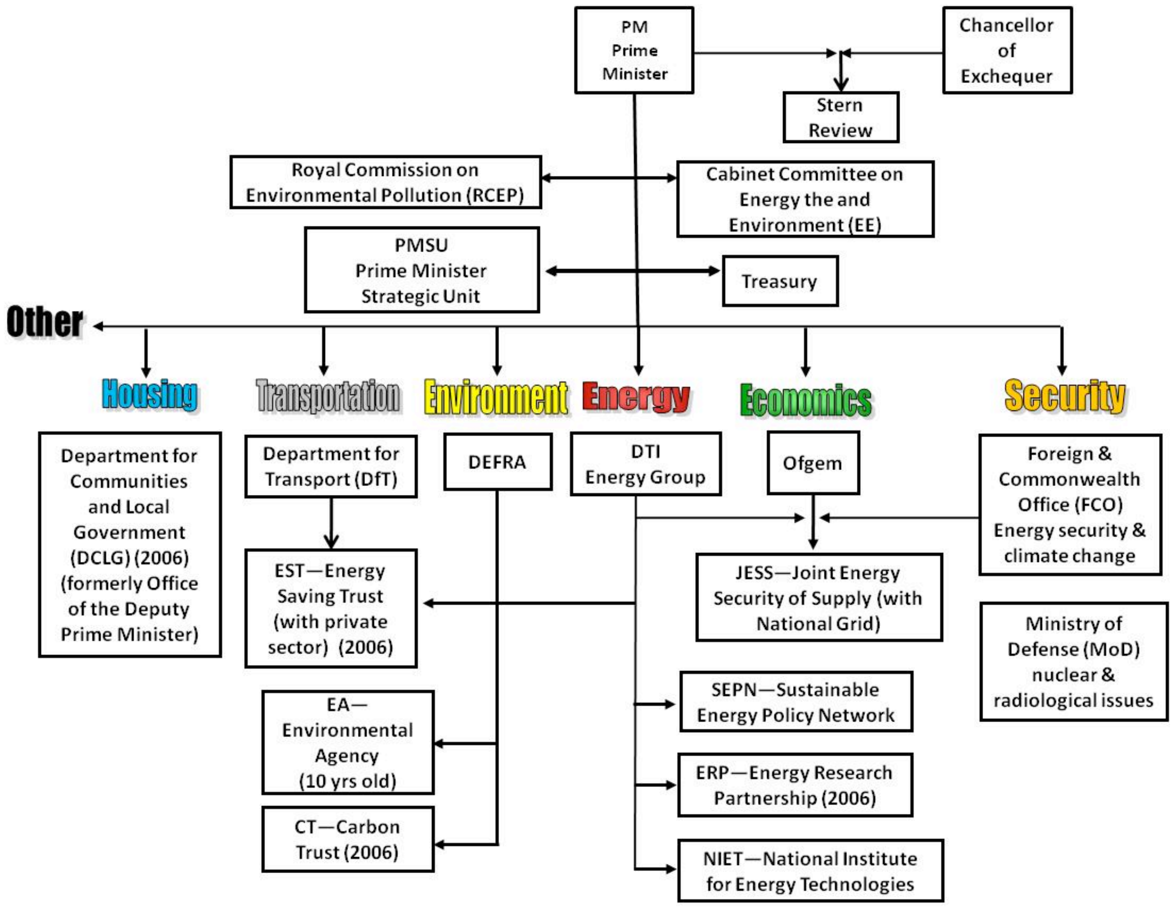
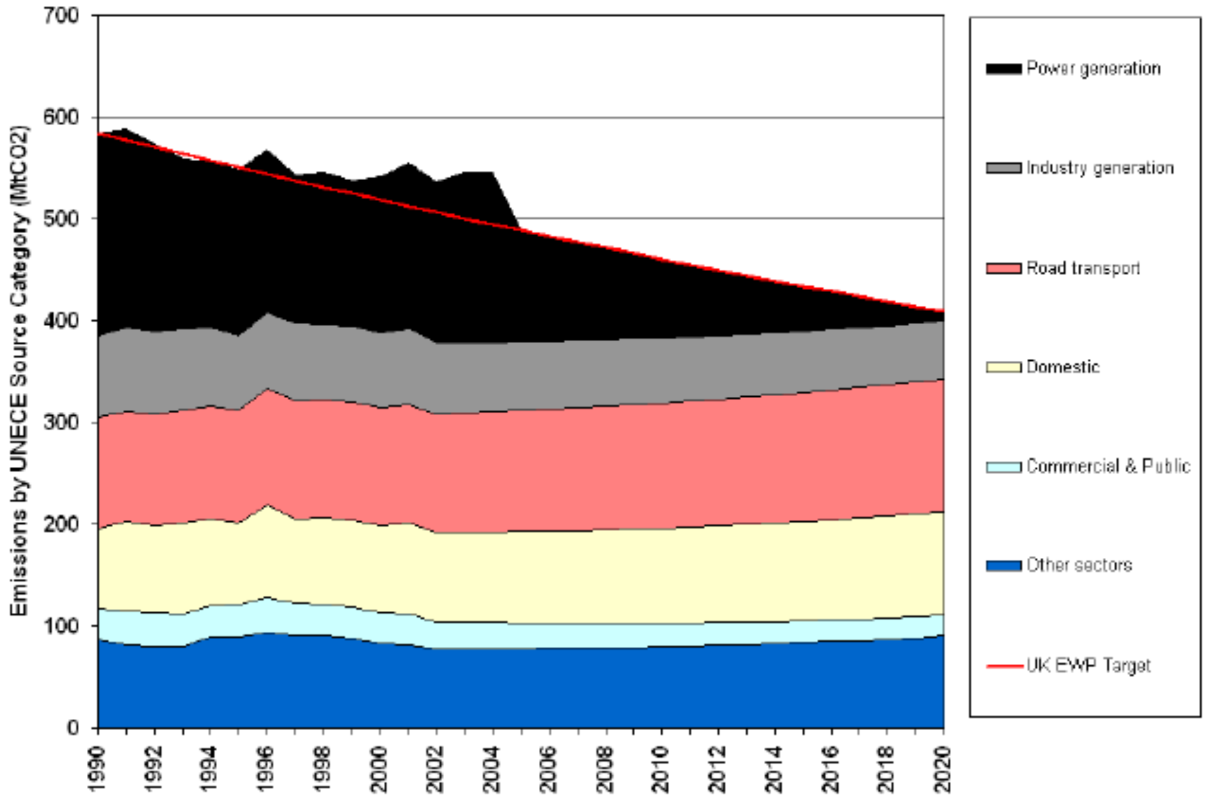



**Figure 3 Energy Policy Influence Mapping**

Since the overarching thesis question is whether UK energy policy will be strategic and stringent enough to force a UK transition, it is important to understand how UK energy policy is developed. The previous influence mapping charts show that the UK has numerous political and agency actors involved in setting energy policy. In fact, the UK may be facing a politically-constrained energy policy environment (Bower, 2004). This politically-constrained policy environment and multiple policy players may have led to an insufficient systems-approach to policy making. For example, current energy policies rely heavily on the electricity sector to reduce $CO_2$ emissions as per Figure 4, from one Oxford University study (Bower, 2004). Figure 4 illustrates the connection between an overly focused electricity policy and reduction of carbon emissions in the electricity sector. Relying solely on the electricity generating sector would create inequities, and also miss major reduction opportunities in other sectors. This approach would not achieve regulatory goals. The UK will need to take a systems view of carbon emission reductions to affect all major polluting sectors and help achieve UK goals of 60% reduction by 2050. The next sections explore energy use by fuel-type and sector—with an emphasis on the power generation and the domestic sector—to evaluate how to focus future policies.




Data: Bower's calculations and forecasts based on emissions data supplied by DEFRA
**Figure 4 UK Actual and Forecast Future Emissions of CO2 by Sector on a Business as Usual Basis** (Bower, 2004)

### 3.2 Current UK Total Electricity and Natural Gas Consumption

The UK has traditionally depended on natural gas for both energy and space heating requirements, but since the 1990's reliance has increased substantially. Total gas and electricity power consumption is depicted by sector in Figure 5. The figure uses a reverse timeline and a non-linear scale to illustrate sharp increases in energy consumption between 1990 and 2000 with slightly decreasing total use between 2000 and 2005. Since 2000, total natural gas and electric energy consumption has slightly decreased from around 1450 to 1430 TWh per year. Over 75% of UK total consumption of electricity and natural gas for the industrial, electricity, domestic, and services sectors is derived from natural gas sources.

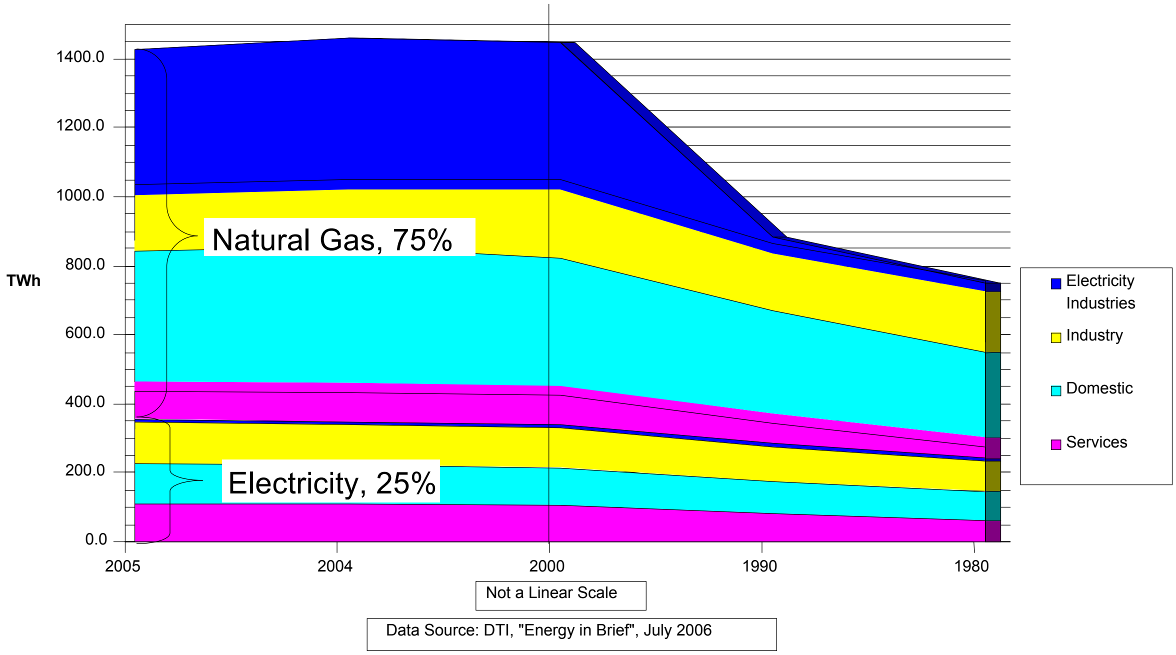



**Figure 5 Total UK Electricity and Natural Gas Consumption (TWh) 1980 to 2005 (DTI, 2006d)**

*3.2.1 Natural Gas*

As seen in Figure 5, in 2005 UK natural gas consumption totaled 1074 TWh with the electricity industries using roughly 427 TWh (40%) followed closely by domestic demand around 382 TWh (36%). Industry used 160 TWh (15%), and the service industry used the least, or 107 TWh (10%), despite the fact that the UK economy is led by the service industry. Domestic gas demand is primarily for space heating and is dependent on winter temperatures and gas prices. Since 2005 was a slightly warmer winter than 2004 and since gas prices rose sharply, there was a 3.5 percent reduction in domestic consumption over 2004. (DUKES, 2005)

*3.2.2 Electricity*

Figure 6 shows the 2005 electricity demand by sector in more detail than Figure 5. In 2005, the industrial sector topped the charts using approximately 1/3 of the total with domestic and service sectors also accounting for approximately 1/3 of total electricity. In 2005, UK electricity demand was approximately 360 TWh, with main supply sources approximately comprising: 123 TWh coal, 74 TWh nuclear, 1 TWh oil, 132 TWH natural gas, 16 TWh renewable, and 14 TWh other, including imports (DTI, 2006c). As shown in Figure 7, the UK consumed just less than 350 TWh of electricity per year in 2000, and just over 350 TWh in 2005. Between 2000 and 2005, electricity use follows a pattern of increasing consumption at a slightly decreasing rate from previous years. Demand is expected to slow down by 2010 and then increase between 2010 and 2020.

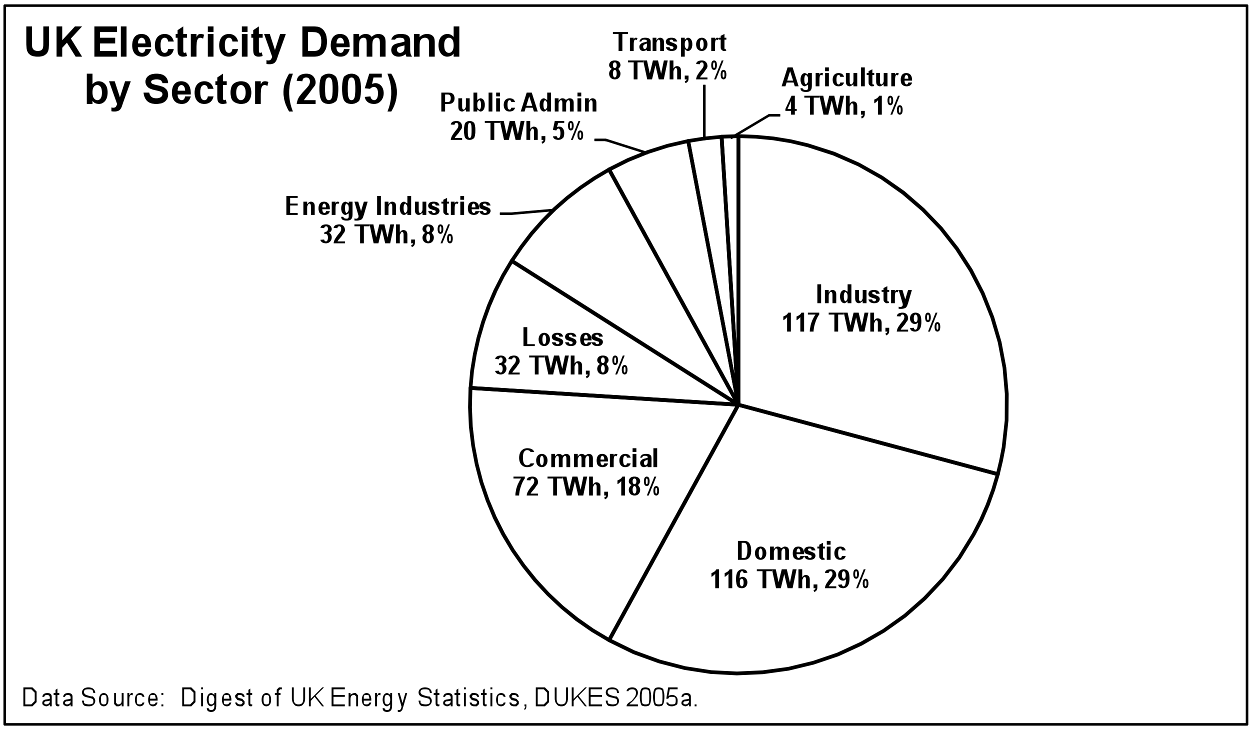



**Figure 6 UK Electricity Demand Breakdown**

### 3.3 Future Electricity Trends

Figure 7 presents DTI's projections of electricity generation and its fuel mix for 2010, 2015, and 2020. The forecast predicts a somewhat disturbing prediction by the DTI for year 2020 natural gas electricity generation—that the current UK natural gas reliance will soon become even more reliant on natural gas imports. With strong growth in natural gas electricity production during times of historically low prices, recent price increases have tightened the gas market leading to higher import prices (DUKES, 2005). This fact alone creates concern; however, uses other than electricity generation account for approximately 60 percent of UK natural gas use (DTI, 2006d). In addition, dwindling North Sea natural gas resources and the energy security issues created by over-reliance on fuel imports mean that the UK should reconsider future dependence. Another concern is that natural gas has an extremely volatile price history in addition to recent high prices.

Discussed further in Chapter 4, many UK nuclear and coal generation plants are scheduled to close or retire by in the next 20 years, and plans are in place to replace capacity primarily with new gas, coal, and some renewable generating capacity (JESS, 2006). The UK government is also reconsidering its nuclear policy to determine if nuclear should play a bigger role in future electricity generation (DTI, 2006d).

Despite recent goals of 20 percent renewable generation, the DTI predicts roughly 14 percent of 2020 electricity demand will be met by renewables (DTI, 2006c). This thesis recommends a 2030 electricity mix, such as the theoretical one depicted in Figure 7 that builds on $CO_2$ goals, existing generation, replacement opportunities for closing plants, Renewable Obligation goals, carbon and fossil fuel price uncertainty and volatility, diversity, and technology innovation to revitalize and rejuvenate the UK's aging energy infrastructure. This would include an electricity generation mix that achieves 30 percent renewables; holds natural gas constant to current output; closes aged nuclear plants and continues operation on the remaining plants; and transitions faster to clean coal including flue gas scrubbing and carbon capture and storage.

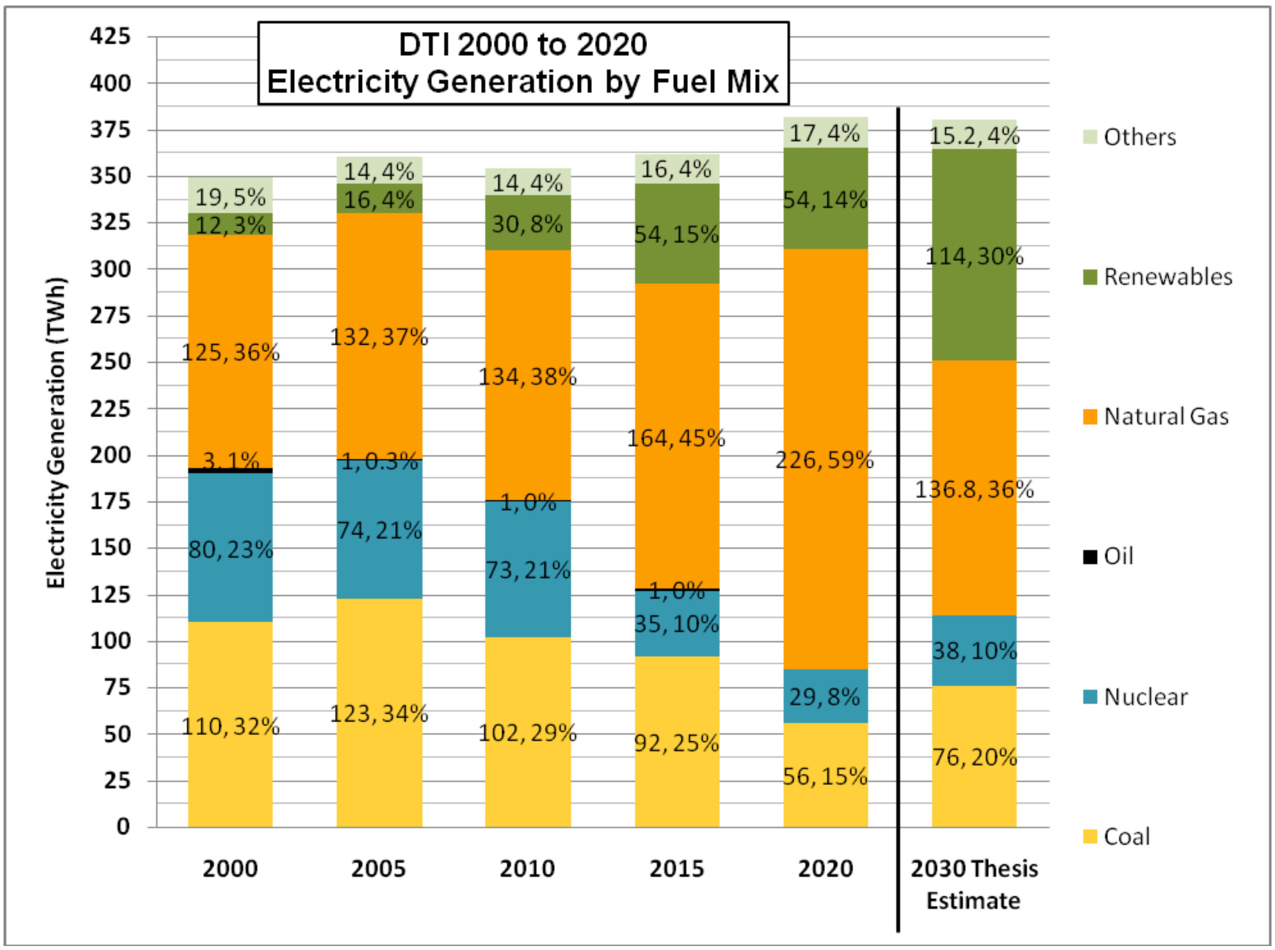



**Figure 7 UK Electricity Generation Fuel Mix (2000 to 2020) (DTI, 2006c)**

### 3.4 UK Energy Security

The Joint Energy Security of Supply Working Group (JESS), in conjunction with the DTI, Ofgem, National Grid, and the Foreign and Commonwealth Office (FCO), is concerned with medium- to long-term energy security (JESS, 2006). Plant margin—the percent of plant capacity that exceeds peak winter demand—is used to quantify supply and demand security (JESS, 2006). The UK historically achieves around or (mostly) above 20 percent plant margin, but JESS maintains that no margin can guarantee that

100 percent of demand would or even should be met (JESS, 2006). In fact, it should be true that decreasing peak winter demand could decrease plant margin requirements. In addition, since thermodynamics dictates that electricity generation operates at approximately 33 percent efficiency, a simple program of increasing energy efficiency would save electricity and increase security. Transmission and distribution losses, as well as inefficient consumption patterns, also decrease efficiency, requiring higher plant margins. Measuring energy security based on plant margin does not recognize the ability of energy efficiency to decrease overall energy needs.

In addition, since fuel prices exhibit volatility, and renewable sources exhibit intermittency, plant margin should not be the only measure of energy security. For example, natural gas currently supplies over 75 percent of UK electricity and space heating needs (See Figure 5) (DTI, 2006d). Natural gas demand is expected to fall slightly and then rise gradually in the next 10 years (JESS, 2006). UK and North Sea supplies have been on the decline since 2000, when the UK became a net importer of natural gas (ibid). By 2020, the UK is expected to import at least 80 percent of natural gas from diverse sources and routes, such as the Norway interconnector and planned upgrades, a planned second interconnector, and various existing and planned liquefied natural gas (LNG) import facilities (ibid). There is also some potential for UK supplies to increase somewhat with high natural gas prices due to competitive extraction (ibid). Gas spot and forward prices are volatile, recently ranging between October 2006 lows of 21p per therm and January 2006 highs of 90p per therm (JESS, 2006). These factors could combine to undermine UK energy security in the likely event of high natural gas prices. These concerns further illustrate the uncertainty in fuel prices and why a mixture of resources should meet energy demands.

The 2006 Energy Review considers clean coal an important contributor to future UK energy (DTI, 2006b). In the UK, coal extraction has fallen from 50 Mt in 1996 to 20 Mt in 2006 (JESS, 2006). Coal extraction and generation also face several environmental challenges, with cost of electricity controlled by current and forward prices. Despite these facts, coal-fired generation supplied approximately one-third of electricity for 2006, rising to 42 percent during the winter (JESS, 2006). In 2016, the EU LCPD will enforce tighter emissions levels for coal plants (Further explained in Chapter 4). LCPD controls are expected to decrease 2020 coal generation to approximately 60 percent of 2005 demand (JESS, 2006). Currently, about 70 percent of coal is imported, which is expected to remain constant through 2020, although later analysis finds clean coal technology combined with UK coal reserves to be cost-competitive in a carbon-constrained economy.

Figure 8 illustrates how coal-fired generation contributes to peak winter demand, while nuclear and natural gas (CCGT) plants tend to operate fairly consistently throughout the year. Unless natural gas reliance is even further increased, Figure 8 provides evidence of a future gap in the electricity sector from coal and nuclear closures through 2030. Since the UK already shows strong reliance on natural gas, clean and sustainable generation is needed to meet emissions targets. For instance, the UK should consider distributed microgeneration to meet domestic, commercial, industrial, public administration, building, and loss sector demand. Since capital investment will be required either way, the UK should invest in all new renewable technologies that rely on readily available sources like solar, wind, waste, and biomass power. Analyzed in Chapter 4, the UK should also consider updating approximately 60 percent of its coal infrastructure to ultrasupercritical pulverized coal plants with flue gas and carbon capture and storage technologies, further explored in Chapter 4. The next section briefly analyzes the electricity market and grid.

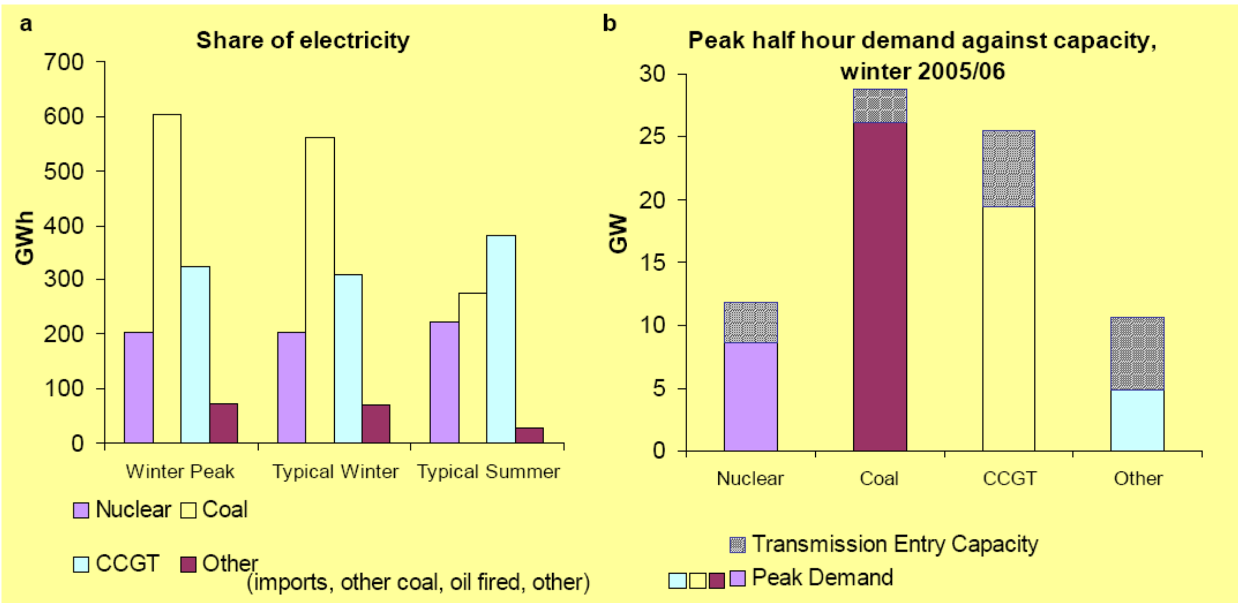



**Figure 8 UK Generation Profile Summer/Winter (JESS, 2006)**

### 3.5 UK Electricity Market and Grid

The April 2005 British Electricity Trading and Transmission Arrangements (BETTA) act created a single UK wholesale electricity market to "promote competition in generation and supply" (DTI, 2005). Wales' and Scotland's electricity markets were incorporated into the England National Grid Company (National Grid), the current UK System Operator (ibid). BETTA manages metering and settlement arrangements to ensure "that all parties pay, or are paid, for the power that they buy or sell" (ibid). Under BETTA, National Grid charges all grid-connected generators for use of any part of the transmission network in the UK (Ford, 2005) and is responsible for holding short-term reserve for uncertain events (JESS, 2006). An extremely liberalized UK energy market has amongst the cheapest domestic and industrial energy prices in the EU, and is driven by market participants commercial decisions (JESS, 2006).

Figure 9 (adapted from (DTI, 2005)) is a simplified map of the UK electricity system and illustrates the physical and commercial supply chains. The commercial chain operates in conjunction with the supply chain to manage power payments, production and demand, transmission and distribution networks payments, and supplier metering. The physical supply chain illustrates the movement of electricity through the grid. BETTA sets the rules to balance supply and demand and "ensure that suppliers, traders and generators bear their fair share of the costs and the benefits (DTI, 2005)." National Grid matches power generation to consumer demand through Balancing Services Use of System (BSUoS) charges to suppliers. It is a complex system with many operational elements that need to be coordinated.

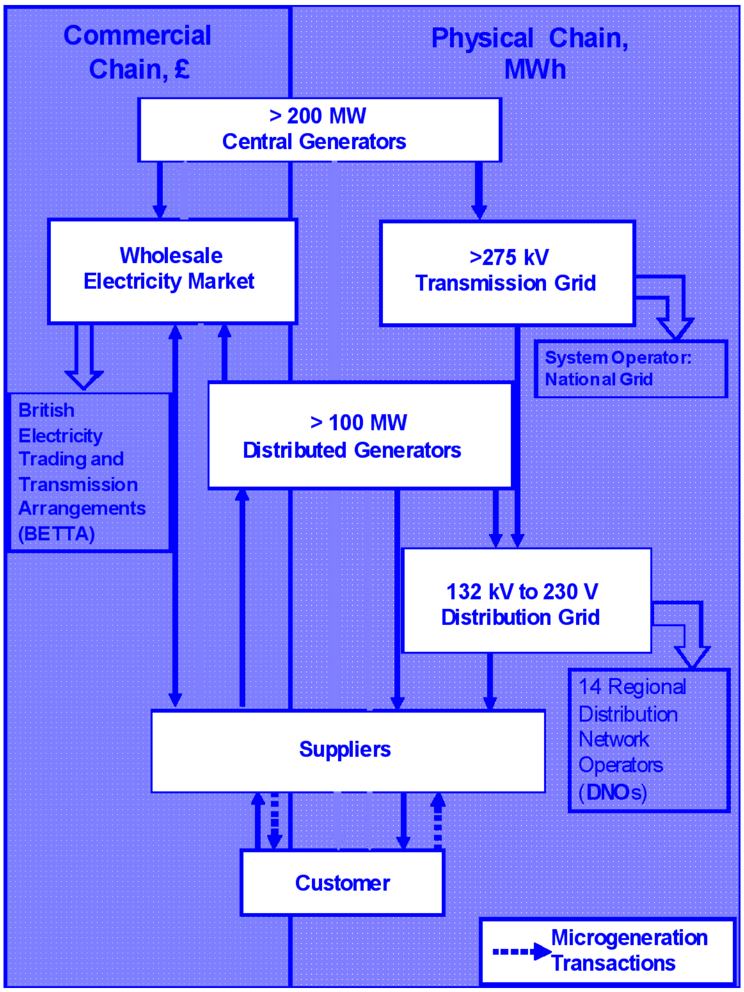



**Figure 9 July 2005 UK Commercial and Physical Supply Chain**

The UK's grid network contains the bulk of major transmission lines (275 and 400 kV) in the south to accommodate population centers. Scotland, with the most wind and hydro renewable resources, has a weak network of 275 kV lines connected to the national grid. These lines are insufficient to carry increasing amounts of wind and hydro power to the southern England population centers. To meet government renewable-generation goals, the Scottish grid network would need further development. A 2003 study by the Transmissions Issues Working Group, with review by an independent technical consultant to DTI, found that 2 to 6 GW of Scottish production would require £520 to £1495 million in grid investment (DTI, 2003b). In addition, England's network is aging and in desperate need of upgrading, which is another costly centralized electricity system project. On November 6, 2006, Engineering News Record reported \$5.3 billion (£2.7 billion) in contracts to upgrade aging transmission networks and to build links to increasing numbers of wind farms and new generating plants (ENR, 2006). This commitment of funds indicates that the UK is serious about meeting renewable goals and customer needs. Unfortunately, it is difficult to determine if the ability of the grid network to accommodate diverse generation technologies has been considered. The work should be carefully analyzed to consider future sustainable generating mixes.

### 3.6 Conclusion

Section 3.1 explored UK energy policy and finds that the disjointed UK energy policy may need to be overseen by one agency with the strength to set and enforce market-wide energy policies in a carbon-constrained economy. This would pull other sectors into the EU ETS, and join all energy-related departments under one management. As noted earlier, agencies have momentum and resist change; therefore, it's likely not necessary to shift employees out of their current locations. How to unify UK energy policy and where to house employees should be studied further before making system-wide changes. If employee morale is destroyed in the process of developing a unified front, the agency will be worthless.

As explored in Section 3.4, the UK's future energy security should not be measured exclusively by plant margins, but should include production diversity, fuel supply, and technology supply. The best approach to energy security is to diversify supply and generation to protect against volatile fossil fuel prices and to control carbon emissions. The UK should use domestically available fuel sources like clean coal, wind, hydro, tidal, and solar. The plan should include replacing closing coal and nuclear plants with sustainable generation technologies, such as clean coal, new nuclear, and renewables. The UK should not rely too heavily on natural gas for electricity and heat generation. As was demonstrated in the winter of 2005/2006 (Figure 8), natural gas prices can sufficiently rise to make coal production cheaper in comparison. In addition, with upgraded, innovative coal-burning and capture technologies, the UK can cleanly burn domestic supplies. Renewables should also play a strong role in diversification since renewable resource supplies are abundant in the UK at much cheaper prices. Chapter 4 explores the impact of clean coal, making recommendations on the UK future electricity mix.

## CHAPTER 4.0—Future UK Clean Coal: To Burn or Not to Burn

> "Simply defined, real options is a systematic approach and integrated solution using financial theory, economic analysis, management science, decision sciences, statistics, and econometric modeling in applying options theory to valuing real physical assets, as opposed to financial assets, in a dynamic and uncertain business environment where business decisions are flexible in the context of strategic capital investment decision-making, valuing investment opportunities and project capital expenditures." (Mun, 2007)
>
> Jonathan Mun, Ph.D., Vice President, Decisioneering, Inc.

Coal, once considered the black gold of the UK, has had a checkered past complete with miner strikes and labor issues, numerous environmental concerns, and an industry transition from government subsidized to a private sector industry. Currently, the EU Large Combustion Plant Directive (LCPD) requires Flue Gas Desulfurization (FGD) technology by 2008 or to close down existing conventional coal plants by 2016 (Jess, 2006). Future carbon prices will likely push the industry to develop Carbon Capture and Storage (CCS) technology and other technology innovations (see Section 2.3). The regulatory hurdles of the Electricity Act and UK planning law will make new conventional coal plant construction approval unlikely (Nuttall, 2007). In addition, uncertainties associated with rising coal costs, a carbon market, declining domestic coal extraction, and energy security make coal plant investment decisions more difficult.

The most pressing issue for the coal industry is how to invest now (by 2008) to meet future environmental regulations in a cost-efficient manner, while also considering the dynamic and uncertain future of coal. Therefore, the UK coal system, with dynamic and uncertain future coal and carbon prices, needs a flexible, systems-analysis approach to capital investment decision-making, especially designed for a system as large as the UK coal system. Real options analysis is one method that can incorporate future fossil fuel and carbon price uncertainties into levelized capital cost calculations of power plants to determine whether to build incremental improvements or to close the plant. This alternative view of business strategy is necessary due to the difficulty of predicting future prices in the coal, electricity, and carbon markets, as well as the interaction between these systems and larger systems like the international energy fuel system and steel industry, as well as the UK electricity and transportation systems.

Coal and carbon price projections are difficult and many predictions are wrong. For instance, fossil fuel price trends are generally incorrect because they assume simplified growth paths, while market forces produce large price swings. Both coal and carbon have a large confidence band of probable prices. Real options techniques provide decision-makers with a learning tool to develop better informed strategic decisions as uncertainties are resolved through time in a dynamic system (Mun, 2007). In other words, the resulting real options decision tree helps business leaders and policy makers form and reappraise their strategies as situations change, which they are almost guaranteed to do.

Chapter 4 explores the UK coal system using a real options binomial lattice tree to represent future coal and carbon prices, including future low-sulfur coal, medium-sulfur coal, and carbon price probability distribution functions (PDFs) to account for future regulatory (carbon and sulfur dioxide) and coal price uncertainties. After generating PDFs, carbon and coal prices were used to analyze and compare several scenarios that account for current and future UK plant owner investment choices in response to the LCPD regulation by considering the cost of FGD retrofit and new build. The analysis compared UK power plant configurations to determine electricity-generating costs per kilowatt-hour (£/kWh) and pollutants per year (tonnes) using the Carnegie Mellon University Integrated Environmental Control Model (IECM). The final step was to input IECM scenario outputs into spreadsheets to calculate and compare:

(1) capital costs,
(2) probable 2030 costs of coal electricity generation, and
(3) emissions levels of carbon dioxide and sulfur dioxide.

Potential power plant configurations are compared to determine coal's optimal contribution to 2030 UK electricity needs. The analysis attempts to address how the UK should dynamically develop their coal system and how to modify existing DTI coal strategies.

Each scenario, explained in detail in Section 4.4, was based on plant retrofit and new plant technology options, as well as multiple 2030 coal and carbon price combinations.

The results conclude that by the year 2030—when the total UK carbon emissions goal is approximately 350 million tonnes (Mt) of $CO_2$ (95 Mt of Carbon)—coal can only be burned cleanly, and would likely do so at a premium price. With carbon and coal prices projected to significantly increase, the price of pollution emissions brings clean coal technology costs in line with conventional coal. For instance, clean coal technology 2030 prices vary from a low of £0.09/kWh up to £0.17/kWh for a subcritical plant retrofit and between £0.10/kWh and £0.16/kWh for a new supercritical plant. The results of the analysis and outcomes were used to compare current and possible power plant configuration plans and the necessary supporting policies.

The major conclusion of the analysis is that when accounting for high carbon and fuel price uncertainties, it is cheaper to build a new supercritical plant than to retrofit an existing plant with FGD and/or CCS. This is especially true for older plants and if the FGD and CCS will be built in stages. In addition, although not analyzed in this thesis, several technologies—renewable, microgeneration, new nuclear—are cost competitive now with new coal power plant's cost of electricity. Therefore, it is a finding of this thesis that the UK should review $CO_2$ policy across all sectors to ensure strong price signals to induce investment in carbon abatement technologies across all energy sectors now. The timing is right because several UK coal plants have plans for immediate-term FGD-retrofit. Instead, stringent UK policy would induce these plant owners to invest in supercritical, clean technology (with FGD and CCS) now in the most long-term cost-effective manner to achieve future energy policy goals. It would also avoid investments in stand-alone FGD-retrofits, a cost-inefficient way to invest in cleaning up plant emissions, and should encourage these plant owners to invest in other, more sustainable technologies and policies, with a focus on distributed generation, renewables, and energy efficiency.

## 4.1 Introduction

The Energy Review reports specify that “clean coal” will have an important and continued roll in UK energy production (DTI, February 2003). According to the DTI, clean pulverized coal includes high-efficiency boilers, co-firing with biomass, and carbon capture and storage (CCS), which secures carbon dioxide emissions and transfers them to an underground geological site (DTI, 2006a). The CCS process has been demonstrated, but is not yet considered fully proven (MIT, 2007). The DTI is committed to developing CCS through demonstration funding of the Carbon Abatement Technology program, a CCS task force, and a formal coal advisory group (DTI, 2006a). In addition, the LCPD has also recently tightened sulfur regulations. Chapter 4 considers existing plant upgrades versus building new efficient supercritical boilers complete with built-in CCS and Flue Gas Desulfurization (FGD) technology.

Compared to oil and natural gas, coal is an abundant and cheap fossil fuel, both in the global market and in the UK. Currently, coal-fired electricity plays a critical role in UK electricity generation, supplying approximately one-third of demand, and often exceeding 40 percent during winter peaks (see Figure8) (JESS, December 2006). Coal-generation plays a strong role in UK energy supply and fuel diversity and offers fast response to system-wide demand since plants can be quickly fired-up.

On the other hand, coal use negatively impacts the environment at each stage of the lifecycle from extraction, transportation, and preparation to energy production. Impacts include human health and safety effects, and environmental externalities from: mining and extracting raw materials; disposing of ash from coal conversion; $SO_x$, $NO_x$, PM, and mercury emissions during fuel cycle; and emissions of global pollutants—$CO_2$ during combustion, and methane from extraction (E&Y, 2005). Despite these strong environmental concerns, the DTI predicts that coal will contribute approximately 15% to the 2020 electricity generation mix (see Figure 7) (DTI, 2006c). Therefore, coal’s contribution to UK electricity generation needs further consideration.

## 4.2 UK Pulverized Coal Plant Technology

Pulverized coal technologies dominate worldwide coal energy production (E&Y, 2005). Figure 10 illustrates a typical pulverized sub-critical coal boiler plant, which achieves around 35% efficiency (CMU, 2006). Cycle efficiency depends on, and is limited by, the temperature of the boiler steam, which is controlled by the temperature and pressure specifications of the boiler’s alloy materials (E&Y, 2005). Current supercritical technologies are approximately 43 percent efficient (CMU, 2006). Recent EU, US, and Japanese R&D programs are studying nickel alloys to bring temperatures up to 700 degrees Celsius, which would increase sub-critical plant efficiencies by about 15% (E&Y, 2005).

The pulverized coal system depicted in Figure 10 is termed “flexible” because several modifications could be implemented to decrease plant emissions. For instance, Flue Gas Desulfurization (FGD) and Carbon Capture System (CCS) retrofits would lengthen the plant’s life by meeting emissions regulations. As discussed above, FGD technology will be required on all coal plants to meet current regulations by 2016, or plants will be forced to close down. FGD uses flue gas cleaning, a costly method that processes large volumes of gas (E&Y, 2005). Current pulverized coal technology also includes hot scrubbing to control NOx, carbon injection for mercury, and cold scrubbing for particulates. Not all existing plants are fitted with these improvements.

There are several available carbon capture methods such as, flue gas separation using chemical absorption, high-oxygen combustion, and pre-combustion capture used in coal gasification power plants (Howard Herzog, 2004). Although it is costly, flue gas CCS is currently the cheapest capture method and uses cold scrubbing of flue gases with solvents to capture, transport, and store $CO_2$ (ibid) (see Figure 11). Amine CCS technology was modeled because it is employed at about a dozen plants worldwide (ibid) and it is the only carbon capture technology in the IECM program. In practice, the captured $CO_2$ is used for industrial and commercial processes, such as the production of urea, foam blowing, carbonated beverages, and dry ice production, which is why chemical absorption is the cheapest capture method (ibid). However, using a life cycle approach means that this carbon will eventually end up in the atmosphere. Therefore, this study is limited by modeling capabilities, but should still represent relative cost scales to help with business and policy decisions.

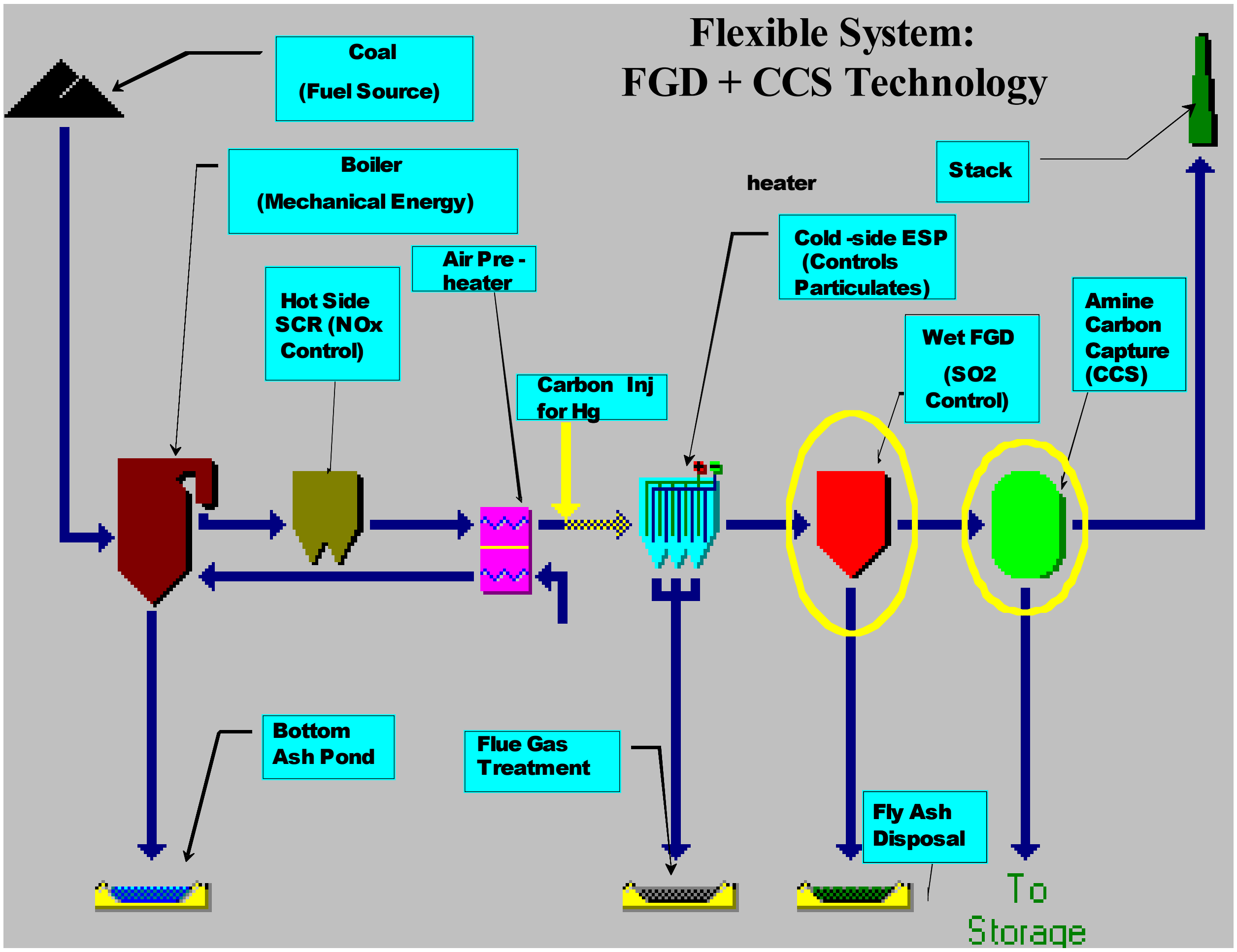



**Figure 11 Pulverized Coal System Components**

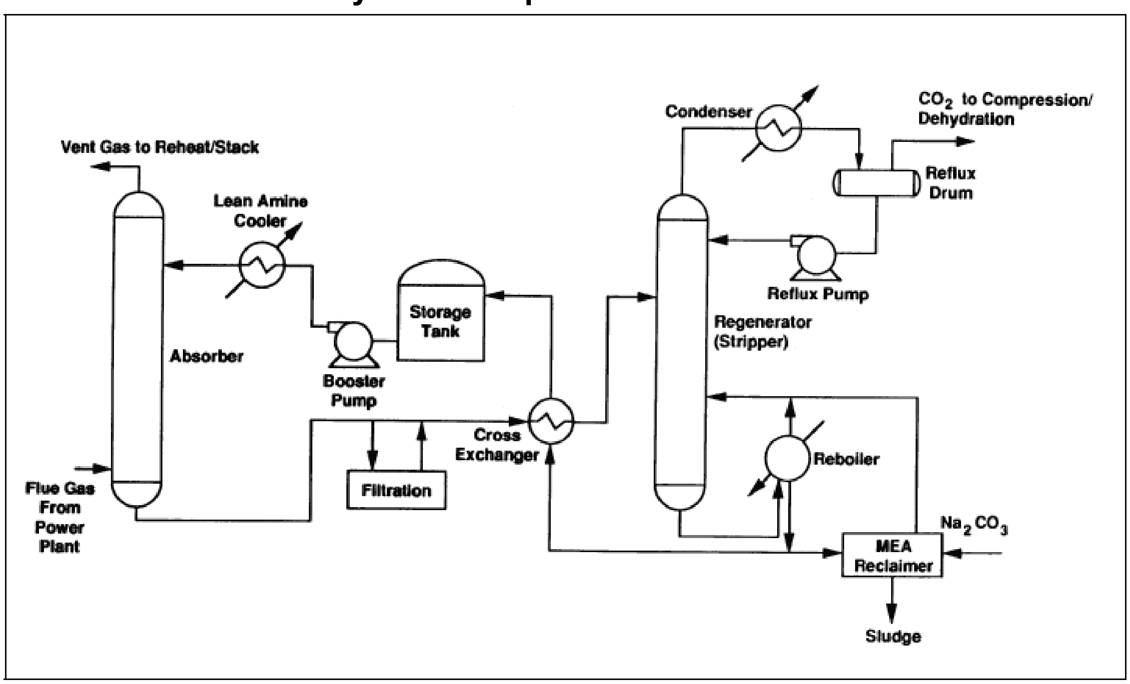



**Figure 10 Process Flow Diagram for the Amine Separation Process**

Table 1 depicts the UK pulverized coal power stations as of December 2006. This system is continuously changing due to plant owner decisions to add FGD technology or to close down by 2016. As shown in the table, most UK boiler units have 500 MW of capacity, and most plants contain more than one, and up to six, boiler units. Total January 2007 pulverized coal capacity is 28.8 GW.

**Table 1 UK Pulverized Coal Power Stations Operating as of December 2006** (JESS, December 2006)

| Station | Number of Units | Capacity (GW) | Capacity per Unit (MW) |
|---|---|---|---|
| Aberthaw | 3 | 1.5 | 500 |
| Cockenzie | 2 | 1.2 | 600 |
| Cottam | 4 | 2 | 500 |
| Didcot A | 4 | 1.2 | 300 |
| Drax | 6 | 3.9 | 650 |
| Eggborough A | 2 | 1 | 500 |
| Eggborough B | 2 | 1 | 500 |
| Ferrybridge (Stack 1) | 2 | 1 | 500 |
| Ferrybridge (Stack 2) | 2 | 1 | 500 |
| Fiddler's Ferry | 4 | 2 | 500 |
| Fifoot Point (Uksmouth) | 3 | 0.4 | 133 |
| Ironbridge | 2 | 1 | 500 |
| Kilroot | 1 | 0.5 | 500 |
| Kingsnorth | 4 | 2 | 500 |
| Longannet | 4 | 2.3 | 575 |
| Ratciffe | 4 | 2 | 500 |
| Rugeley | 2 | 1 | 500 |
| Tilbury | 3 | 1 | 333.3 |
| West Burton | 4 | 2 | 500 |
| **Total** | **58** | **28.0** | **480** |

### 4.3 Introducing Uncertainties

Supporters of real options analysis apply the process to develop frameworks for large investment decisions, since the process accounts for risks and future uncertainties. This chapter uses real options methods because future coal and carbon prices are difficult to predict, and since many past projections of future fossil fuel prices have proven to be gross underestimations. For instance, fossil fuel price trends are generally incorrect because they assume simplified growth paths, while market forces produce large price swings. Both coal and carbon have a large confidence band of probable prices. Real options techniques provide decision-makers with a learning tool to develop better informed strategic decisions as uncertainties are resolved through time in a dynamic system (Mun, 2007). In other words, the resulting real options decision tree helps business leaders and policy makers form and reappraise their strategies as situations change, which they are almost guaranteed to do.

A binomial lattice model (further explained in Section 4.4) considers past volatility and standard deviation of past prices to calculate future expected prices; that is, the analysis specifically considers uncertainty and risk to determine what future prices might be. The binomial lattice modeling result, a probability distribution function (PDF), was used to determine low, mean, and high price scenarios and considered the risk of high prices for plant configuration decision-making. Further explained next, the range of potential low and medium sulfur coal prices, as well as future carbon prices, were determined to account for no-FGD/CCS, FGD-retrofit, CCS-retrofit, and new plant scenarios.

### *4.3.1 UK Coal Situation—Supply, Quality, and Prices*

In the 70's, coal production was at a high, but recently only 9 working pits with troubled financial pasts and less than 6000 employees exist in the UK (Pym, 2004). Once considered black goal in the UK, most of today's industry is owned and operated by the private company, UK Coal (ibid). Today's coal industry is a trace of what it was before the miners' strike in 1984, when there were 180,000 miners working at 170 pits (ibid). Official strike action began in March 1984, when miners in five pits in Yorkshire and Scotland believed that the pit closures were not properly reviewed (Harris, 1984). The strike was supported by the National Union of Mineworkers (NUM), which meant miner support across the UK (ibid). Under Conservative Government leader, Margaret Thatcher, the High Court seized the NUM funds in October 1984 (ibid). In addition, a police force was mobilized to deal with "illegal public disturbances" related to the strike (ibid). Thousands of miners lost their jobs permanently, and others were denied state benefits (ibid). In the end, one year after initiating the strike, the NUM conceded defeat (ibid). Figure 12 shows the devastating impact on the coal extraction industry in the UK.

LCPD emission control limits eventually require FGD with a maximum of 1.8% sulfur, or without FGD to burn 0.18% sulfur coal (MottMacDonald, 2004). Sulfur levels in domestic UK coal average approximately 1.7 to 1.8% (ibid). Due to the high costs of washing fines to remove sulfur, UK coal has little potential for use in non-FGD power plants. The UK has the prospect to export non-compliant coal internationally, but this market could shrink as local sulfur regulations tighten, unless foreign plants are equipped with FGD technology. On the other hand, stringent sulfur regulations would likely induce technology innovation for more cost-efficient sulfur control or could push the market to substitute a more sustainable technology (see Section 2.3). LCPD regulation drives the current UK coal demand prospects: (1) burn UK coal only in plants fitted with FGD technology, (2) potentially export coal on the global market, (3) an uncertain future coal market, and (4) an uncertain domestic and international regulatory environment.

With future plant operating costs are heavily dependent on fuel costs, it is important to analyze future coal price-impacts. In the UK, power stations account for approximately 90% of coal consumption (ibid). Coal imports accounted for over 70% of UK coal demand in 2005, while production of coal in the UK continues to decline (Jess, 2006). Since UK electricity industry privatization, the UK coal industry is increasingly influenced by the global coal market (ibid). In 2004, the international market had delivered prices close to record levels due to high demand in 2003 (ibid). Prices are expected to decline over the next decade to levels above pre-2003 prices (ibid). According to the DTI international imported steam coal traded around £25/tonne in 2003, but rose strongly in 2004 and peaked at £37/tonne; between 2004 and 2005, prices fell back to £32/tonne (DTI, 2007a). In other words, prices received by UK producers for sales to generators have been in the range £26/tonne to £29/tonne over the period 2003-2005 (ibid).

The US Energy Information Administration (EIA) website contains coal spot prices, futures, and historical trends (EIA, 2007). Coal prices were fairly stable from 1990 to 2002; however, prices and volatility rose significantly after 2003 influenced by: market, political, and institutional failures, as well as supply and demand side factors, including physical availability, natural disasters, transportation, political situations, carbon and pollution regulation, consumer willingness to pay for cleaner products, and availability of substitutes (ibid). Since coal trades on a global market and since UK past price performance is similar to the detailed EIA data and much harder to access, US prices have been used to approximate UK coal prices. In addition, the starting price of coal is an input in the binomial lattice tree that is simple to change to update market conditions as they change. Therefore, the analysis can be changed at any time due to a wide fluctuation in market conditions. EIA data, at the time of analysis and adjusted for current exchange rates, generated analysis of prices in the range of £20/tonne to £27/tonne (ibid).

#### *4.3.2 Emissions Regulation*

UK regulations require Best Available Techniques Not Entailing Excessive Cost (BATNEEC) standards. New plant pulverized coal sulfur BAT is Flue Gas Desulfurization (FGD) technology. Modeling of existing and proposed power plants, including the FGD technology, was based on the following UK overlapping emissions rules, which are the main constraints on coal burn:

- National Emission Ceiling Directive (NECD) – which sets UK-wide all-installations cap on $SO_2$, NOx, and particulates for 2010;

- Revised Large Combustions Plant Directive (LCPD) – which sets station and company level annual emissions caps on $SO_2$, NOx, and particulates, beginning 2008;

- Ambient air quality standards which set maximum levels of concentration of acid gases and particulates in local air (MottMacDonald, 2004), and

- Potential future EU ETS market trading price and National Allocation Plan (NAP) permit appropriation influence of higher future carbon prices.

The first three regulations, enforced under the UK Pollution Prevention and Control (PPC) regulation, were introduced in 2000 as a result of the EU Integrated Pollution Prevention and Control (IPPC) Directive. For instance, NECD imposes significant caps on $SO_2$, $NO_x$, and particulates for 2010 and aims to limit UK coal burn by significantly raising the cost of producing power. In addition, the 2005 ambient air quality standards will restrict most non-FGD coal units to burn very low sulfur coal, which requires plant upgrades to combat high combustion volatility. Very low sulfur coal, imported from Indonesia, also exhibits even more volatile price characteristics than medium sulfur coal. (MottMacDonald, 2004)

Under the Large Combustion Plant Directive (LCPD), a plant has three choices: (1) comply with the Emission Limit Value (ELV) by 2008, (2) comply with the National Emission Reduction Plan (NERP) 2008, or (3) opt-out (close down) by 2016. Under ELV, existing plants must meet current new plant emission SOx standards of 400 $mg/NM^3$. NERP caps total emissions from the coal power industry. Both ELV and NERP would require FGD technology or a switch to very low sulfur coals by 2008. If a plant opts out due to high retrofit costs, the plant must close by 2016, limiting operating hours to 20,000 hours between 2008 and 2015. (MottMacDonald, 2004) Table 2 describes the current plant status regarding LCPD regulation (JESS, 2006). Any of the 8,200 MW that have chosen to opt-out could continue to operate for 20,000 hours to the end of 2015 (ibid). The table shows that approximately 30 percent of existing coal capacity will be lost due to the LCPD regulation. The next section discusses the impact on carbon prices from the EU ETS.

**Table 2 December 2006 UK Power Plant Status**

| UK Pulverized Coal Power Stations Status under the Large Combustion Plant Directive | | | |
|---|---|---|---|
| **Station** | **Insalled Capacity (MW)** | **FGD Opted-In (MW)** | **FGD Status as of January 2007** |
| **Aberthaw** | 1,500 | 1,500 | Fit by 2008 |
| **Cockenzie** | 1,200 | - | Opt-out |
| **Cottam** | 2,000 | 2,000 | Fit by 2007 |
| **Didcot A** | 1,200 | - | Opt-out |
| **Didcot B*** | 800 | - | Opt-out |
| **Drax** | 3,960 | 3,960 | Complete |
| **Eggborough** | 2,000 | 2,000 | 1/2 Complete, Will fit other 1/2 |
| **Ferrybridge** | 2,000 | 1,000 | 1/2 Units by 2008 |
| **Fiddler's Ferry** | 2,000 | 2,000 | Fit by 2008 |
| **Fifoot Point (Uksmouth)** | 400 | 400 | Complete |
| **Ironbridge** | 1,000 | - | Opt-out |
| **Kilroot** | 500 | 500 | Fit by 2007 |
| **Kingsnorth** | 2,000 | - | Opt-out |
| **Longannet** | 2,304 | 2,304 | Fit by 2008 |
| **Ratciffe** | 2,000 | 2,000 | Complete |
| **Rugeley** | 1,000 | 1,000 | Will fit |
| **Tilbury** | 1,000 | - | Opt-out |
| **West Burton** | 2,000 | 2,000 | Fit |
| **Total** | **28,064** | **20,664** | **Opt-out 7,400 MW** |
| **Source: Compiled from (JESS, 2006)** | | | |

### *4.3.3 Carbon Prices*

Carbon prices are one of the most uncertain commodity prices on the market today, due to the market's newness and price uncertainties. Carbon dioxide, a pollutant that largely influences global climate change levels, is steeped in uncertainties of impacts of changing temperatures. The European Union (EU) Directive 2003/98/EC and Amendment 2004/101/EC established the EU Emissions Trading Scheme (ETS) for reducing carbon emissions and mitigating climate change uncertainties (EC, 2006). Over 10,000 energy and industrial sector emissions levels—that collectively contribute almost 50 percent of EU $CO_2$ emissions—are covered under the trading scheme (ibid). The ETS goal is to cost-effectively comply with Kyoto Protocol commitments (ibid).

One emission allowance, the trading 'currency' of the ETS, allows one tonne of $CO_2$ emission. Allowances are distributed according to approved Member State

National Allocation Plans (NAP), which establish individual installation allocation allowances. These allowances can be used, traded, or banked for future use. Based on the established cap (i.e. the stringency of the regulation), individual installations have a choice to buy allowances, upgrade technology, or switch fuels. The ETS will soon enter its second phase of trading for 2008 to 2012, concurrent with Kyoto Protocol timelines. The European Commission (EC) recently approved the phase two NAPs, although many Member State allocations are still being settled. The third trading period begins in 2013, and the European Parliament and Council of Ministers are undertaking a consultation review of the ETS Directive. A stakeholder working group will submit the main findings by June 30, 2007, which will be followed by the EC legislative proposal. (EC, 2006)

#### *4.3.4 Spark and Dark Spreads*

A study for the DTI has analyzed the impact of carbon trading on historic wholesale prices and to what extent the price of carbon has been passed on to the consumer through the wholesale price (IPA, 2005). Specifically, the study examines the correlation between carbon prices and the spark and dark spreads (ibid). The spark spread is used for natural gas and assumes a typical efficiency of 50% (ibid). It is calculated as the price of power minus the cost of gas to generate a unit of electricity (ibid). The dark spread is calculated the same for coal power, except it assumes 35% efficiency (ibid). These spreads indicate the margin over the costs of fuel that remain for the plant operators (ibid). Carbon can be considered as one of these margins, therefore, the spread can compared against carbon costs to determine the level of costs that are passed along (ibid). Electricity price volatility can be directly correlated with electricity and fuel prices and their corresponding volatilities (Nuttall, 2007). In the UK, there has historically been a highly correlated spark spread, while the dark spread has been less correlated (ibid) (IPA, 2005). This indicates that coal markets are not as liquid as gas, nor as volatile since coal can be stored to wait out price spikes (IPA, 2005).

### 4.4 Scope of Analysis

Figure 12 depicts the real options investment strategic plan analyzed for this Thesis. Each coal plant owner has to make the decision to opt-in or opt-out of LCPD. If the plant owners opt-in, standards are met by installing FGD or burning very low sulfur coal. If the plant owner decides to retrofit with FGD technology, the next decision is whether to install CCS technology to the plant. If the plant owner decides to opt-out, they will have the options of just closing the plant, building a new supercritical plant, or investing in other electricity generating options. If the owner decides to build a supercritical plant (necessarily equipped with FGD technology), the final decision is whether to install CCS technology. The real options analysis in this chapter will consider the five resulting scenarios:

1. LCPD opt-in: burn very low sulfur coals
2. LCPD opt-in: FGD retrofit, no CCS

3. LCPD opt-in: FGD and CCS retrofit
4. LCPD opt-out: new supercritical plant, no CCS
5. LCPD opt-out: new supercritical plant, including CCS

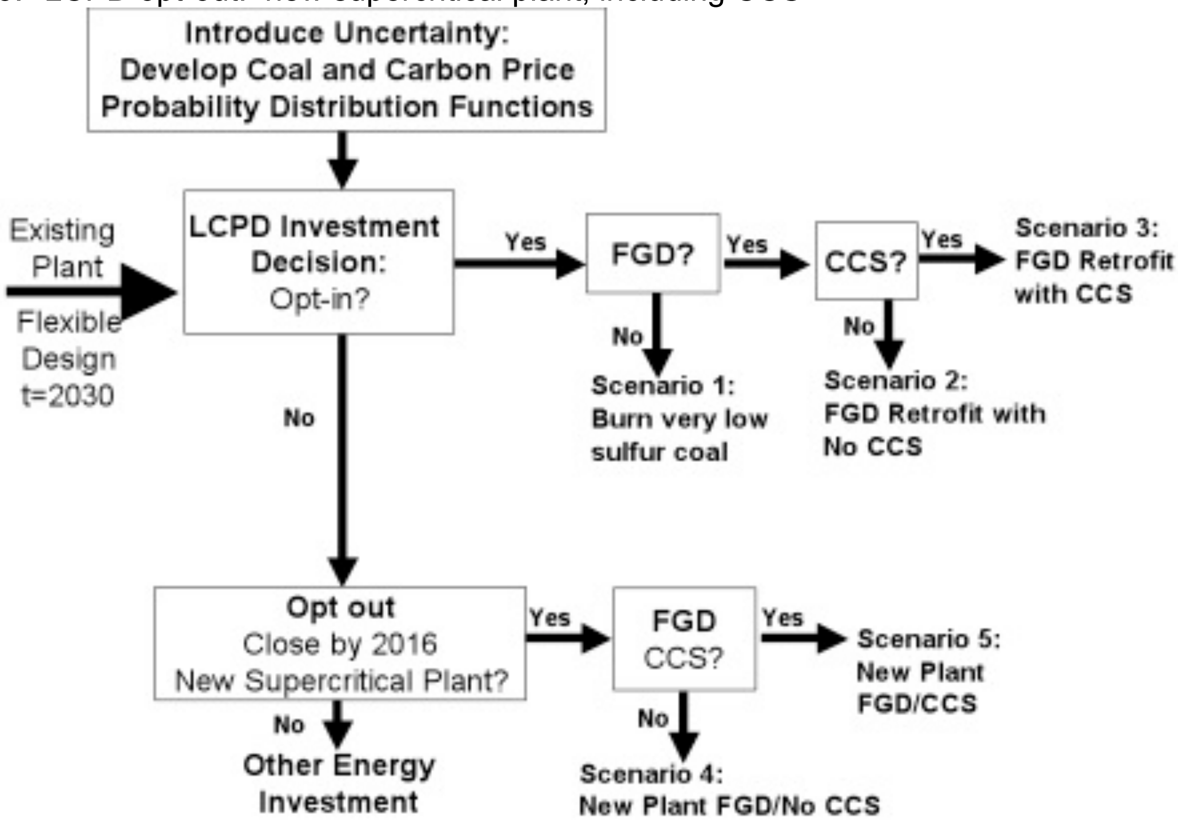



**Figure 12 Study Process: Coal Power Plant Investment Strategic Plan**

To conduct the real options analysis, the first step was to run the binomial lattice models to determine low, mean, and high year 2030 carbon prices, and the same for low and medium sulfur coal prices. The next step was to analyze existing power plants based on the five scenarios to determine electricity-generating costs per kilowatt-hour (£/kWh). If the plant has opted into the LCPD, the model process conservatively assumes paid-off initial capital investments and levelized retrofit and plant operating costs over a 30-year life. If the plant opts out, a scenario is considered where electricity generation costs of a new supercritical plant with and without CCS incur over a 50-year plant life.

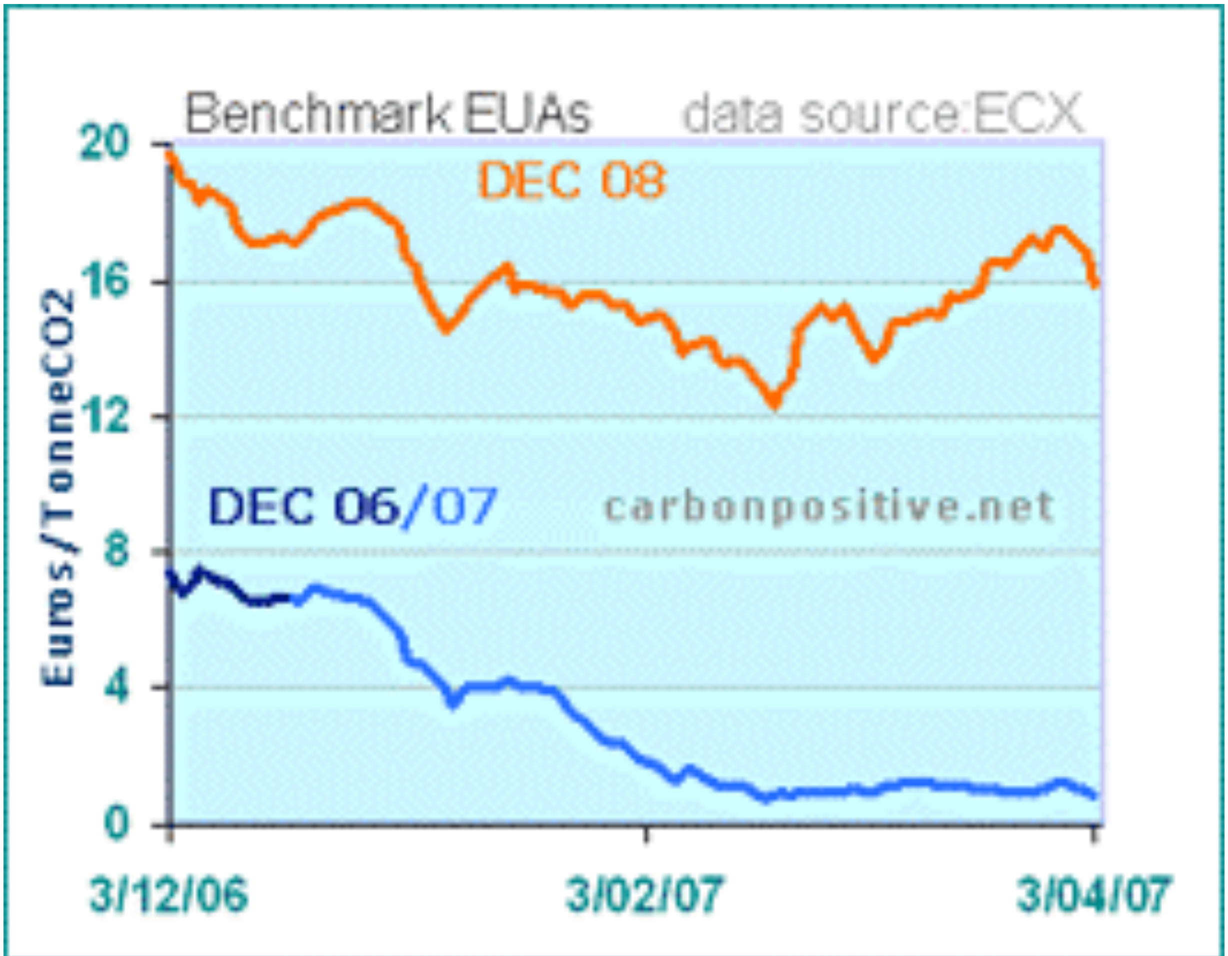
*4.4.1 Lattice Analyses of the Evolution of Major Uncertainties*

To address uncertainty and to develop probability distribution functions (PDFs) for low and medium sulfur coal, as well as EU ETS carbon prices, three lattice analysis models were built. Binomial lattices are easy to build and understand, and are extremely flexible. The same lattice model can be tweaked at any time as more information becomes available about volatility, mean prices, and standard deviations. The lattice tree can also be modified to include infinite steps, which would provide a more precise answer. On the other hand, the simplicity of the model is also its weakness.

The lattice analysis was used to calculate the probability of price distributions over a 25-year time period. Although three lattices were built and all three results will be presented, this section will only include the detailed process only for the carbon price uncertainty PDF. Appendix A includes the detailed process for the low and medium sulfur coal binomial lattice distributions.

#### *4.4.1.1 Calibrate the Lattice*

The historical prices for carbon, Figure 13, are based on two years of EU ETS trading, as well as available future prices to date; therefore, volatility (v) and standard deviation (σ) values were calculated from limited historical data Phase I data, in addition to an uncertain future Phase II ETS allowances. This means that as more trading experience occurs, the binomial lattice should be updated to consider updated volatility and standard deviation calculations. The standard deviation and mean calculations were, respectively, (€6.97 (£4.70) and €17.32 (£11.60)) (Figure 13). Futures prices were also included to improve the accuracy of the calculation. The results show high volatility (v) of 12.4 percent per year, which is equivalent to the average growth rate, also referred to as the interest rate.



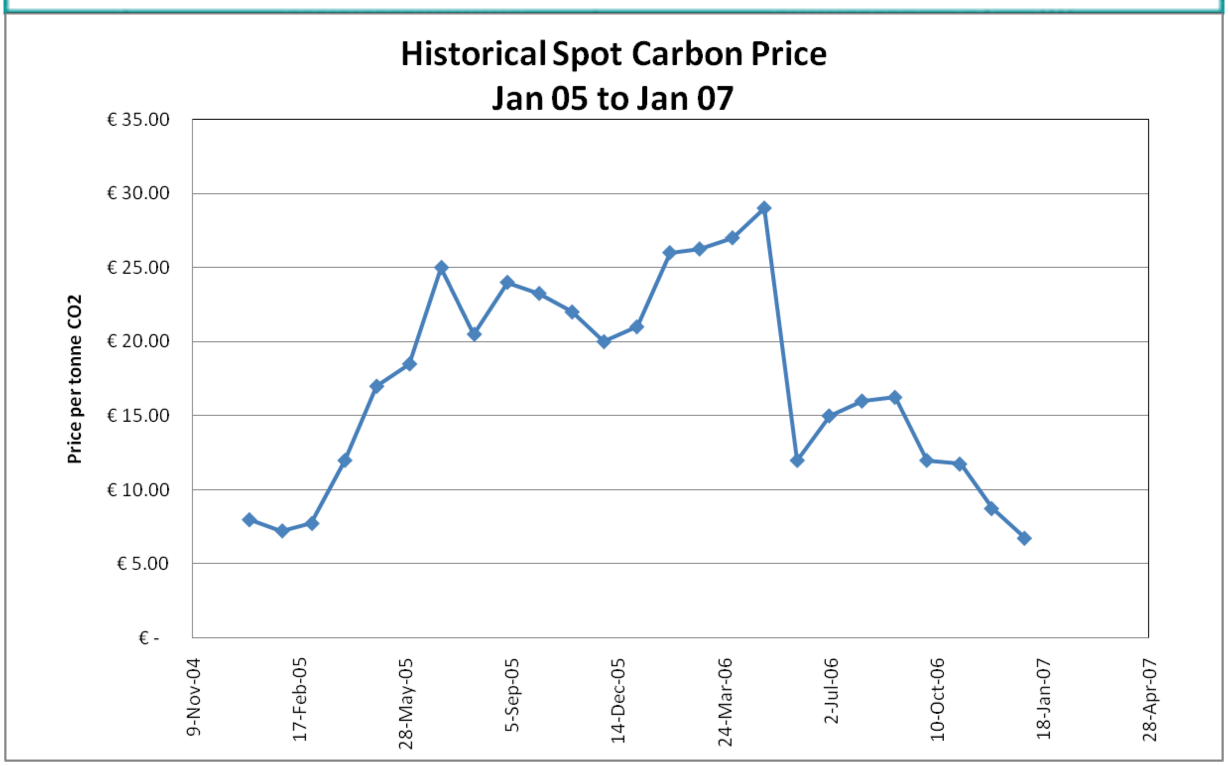




**Figure 13 Futures between December 06 and April 08 and Carbon Prices between January 2005 and January 2007** **Data source: Carbon Positive and ECX**

*4.4.1.2 Calibrate the Lattice*

The lattice model, calculated using a spreadsheet model, begins with the initial price, equal to January 2007 carbon prices of approximately £4.55 per tonne. It is developed for the 25 one-year time periods using the following equations:

$$u = e^{\sigma\sqrt{\nabla t}}$$

$$d = e^{-\sigma\sqrt{\nabla t}}$$

$$p = 0.5 + 0.5(v / \sigma)\sqrt{\nabla t}$$

Where, for January 2007 carbon conditions,

(1) up = **1.330 = u**
(2) down = **0.752 = d**
(3) probability = **0.717 = p**
,
where, Δt = 1 year, v = 12.4 percent, and σ = 28.5 percent.

Appendix A illustrates the application of the probability factor, p, and the up and down coefficients to determine the probability of each node occurring. The lattice steps, expanded over a 25-year period, determined the price of carbon accounting for uncertainty. The Appendix A figures depict the price variations for the 25-year period for selected steps of the process. Table 3 shows the lattice analysis results for low sulfur coal, medium sulfur coal, and carbon dioxide prices.

**Table 3 Year 2030 Price Probability Distribution Functions (PDFs)**

| Low Sulfur Coal | | Medium Sulfur Coal | | Carbon Dioxide | |
|---|---|---|---|---|---|
| Price | Probability | Price | Probability | Price | Probability |
| £ 489.76 | 0.00 | £ 316.98 | 0.00 | £3,194.64 | 0.000 |
| £ 380.76 | 0.00 | £ 249.34 | 0.00 | £1,806.65 | 0.004 |
| £ 296.03 | 0.01 | £ 196.14 | 0.00 | £1,021.71 | 0.019 |
| £ 230.14 | 0.03 | £ 154.29 | 0.01 | £ 577.80 | 0.052 |
| £ 178.93 | 0.06 | £ 121.37 | 0.02 | £ 326.76 | 0.102 |
| £ 139.11 | 0.11 | £ 95.47 | 0.04 | £ 184.79 | 0.153 |
| £ 108.15 | 0.16 | £ 75.10 | 0.08 | £ 104.50 | 0.181 |
| £ 84.08 | 0.18 | £ 59.08 | 0.12 | £ 59.10 | 0.174 |
| £ 65.37 | 0.16 | £ 46.47 | 0.16 | £ 33.42 | 0.137 |
| £ 50.82 | 0.13 | £ 36.56 | 0.17 | £ 18.90 | 0.090 |
| £ 39.51 | 0.08 | £ 28.76 | 0.15 | £ 10.69 | 0.050 |
| £ 30.72 | 0.05 | £ 22.62 | 0.11 | £ 6.04 | 0.023 |
| £ 23.88 | 0.02 | £ 17.79 | 0.07 | £ 3.42 | 0.009 |
| £ 18.57 | 0.01 | £ 14.00 | 0.04 | £ 1.93 | 0.003 |
| £ 14.43 | 0.00 | £ 11.01 | 0.02 | £ 1.09 | 0.001 |
| £ 11.22 | 0.00 | £ 8.66 | 0.01 | £ 0.62 | 0.000 |
| £ 8.72 | 0.00 | £ 6.81 | 0.00 | £ 0.35 | 0.000 |
| £ 6.78 | 0.00 | £ 5.36 | 0.00 | £ 0.20 | 0.000 |
| £ 5.27 | 0.00 | £ 4.22 | 0.00 | £ 0.11 | 0.000 |
| £ 4.10 | 0.00 | £ 3.32 | 0.00 | £ 0.06 | 0.000 |
| £ 3.19 | 0.00 | £ 2.61 | 0.00 | £ 0.04 | 0.000 |
| £ 2.48 | 0.00 | £ 2.05 | 0.00 | £ 0.02 | 0.000 |
| £ 1.93 | 0.00 | £ 1.61 | 0.00 | £ 0.01 | 0.000 |
| £ 1.50 | 0.00 | £ 1.27 | 0.00 | £ 0.01 | 0.000 |

The following probability distribution function, Figure 14, graphically illustrates the potential costs of carbon dioxide per tonne and associated probabilities at years 5, 10, 15, 20, 23 (2030), and 25.

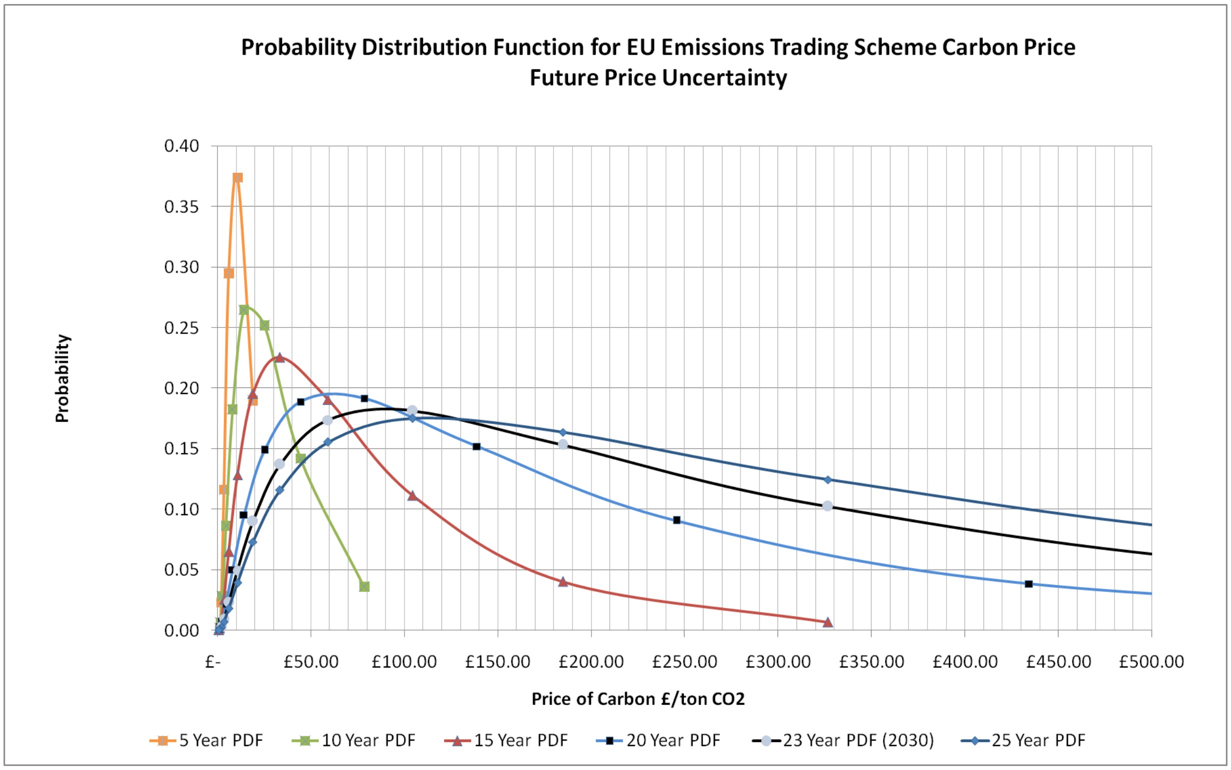



**Figure 14 PDFs for Price of Carbon**

Since the price of carbon dioxide is volatile, it is likely that the prices will vary considerably from year to year with a general uptrend. The PDFs depicted in Figure 14 and the moving mean price from Figure 15 confirm expectations that carbon prices will increase over time with wider spreads of prices and probabilities. Year 23 low, mean, and high prices (Table 4) were used as model inputs for the next step of analysis.

**Table 4 Carbon Dioxide Prices for Selected Years**

| | Year 0 | Year 5 | Year 10 | Year 15 | Year 20 | 23 (Year 2030) | Year 25 |
|---|---|---|---|---|---|---|---|
| **Std Dev** | £ 1.30 | £ 2.80 | £ 6.04 | £ 13.03 | £ 28.14 | **£ 44.65** | £ 60.75 |
| **Min** | £ 0.66 | £ 1.42 | £ 3.07 | £ 6.63 | £ 14.32 | **£ 22.72** | £ 30.91 |
| **Mean** | £ 4.55 | £ 9.81 | £ 21.19 | £ 45.74 | £ 98.73 | **£ 156.67** | £ 213.15 |
| **Max** | £ 8.43 | £ 18.20 | £ 39.30 | £ 84.84 | £ 183.15 | **£ 290.63** | £ 395.39 |
| **For Use in the IECM model** | | | | | | **$ 48.16** | **Min** |
| Exchange Rate 1.92308 | | Tonne Rate 1.102312 | | | | **$ 332.12** | **Mean** |
| | | | | | | **$ 616.08** | **Max** |

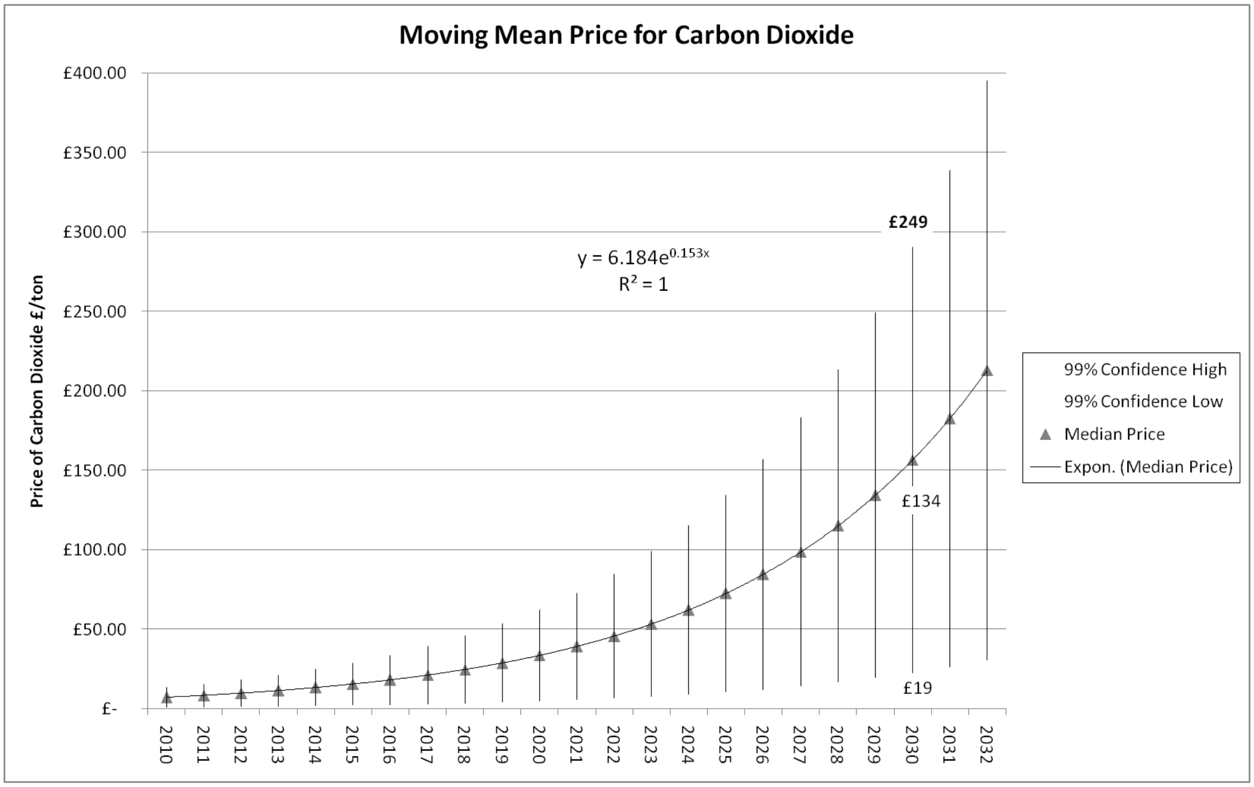



**Figure 15 Carbon Dioxide 25 Years of Mean Prices**

### *4.4.1.3 The Lattice Results for Low and Medium Sulfur Coal*

The price of coal is also volatile; therefore, similar outcomes of price distributions were expected. The PDFs depicted in Figure 16 thorough Figure 18 confirm that coal prices will increase over time with wider spreads of prices and probabilities. Year 23 low, mean, and high prices (

Table 5) were used as basic IECM inputs. The same process was used for both low and medium sulfur coal to derive the following graphs.

**Table 5 Low and Medium Sulfur Coal Prices**

| | **Year 2030 Price (£/tonne or \$/ton)** | | **Year 2030 Price (£/tonne or \$/ton) (used as IECM inputs)** | |
|---|---|---|---|---|
| | **Medium Sulfur Coal** | **Low Sulfur Coal** | **Medium Sulfur Coal** | **Low Sulfur Coal** |
| **Minimum** | £ 27.69 | £ 56.60 | **\$ 58.69** | **\$ 120.00** |
| **Mean** | £ 43.26 | £ 90.95 | **\$ 91.70** | **\$ 192.80** |
| **Maximum** | £ 58.83 | £ 125.29 | **\$ 124.72** | **\$ 265.59** |

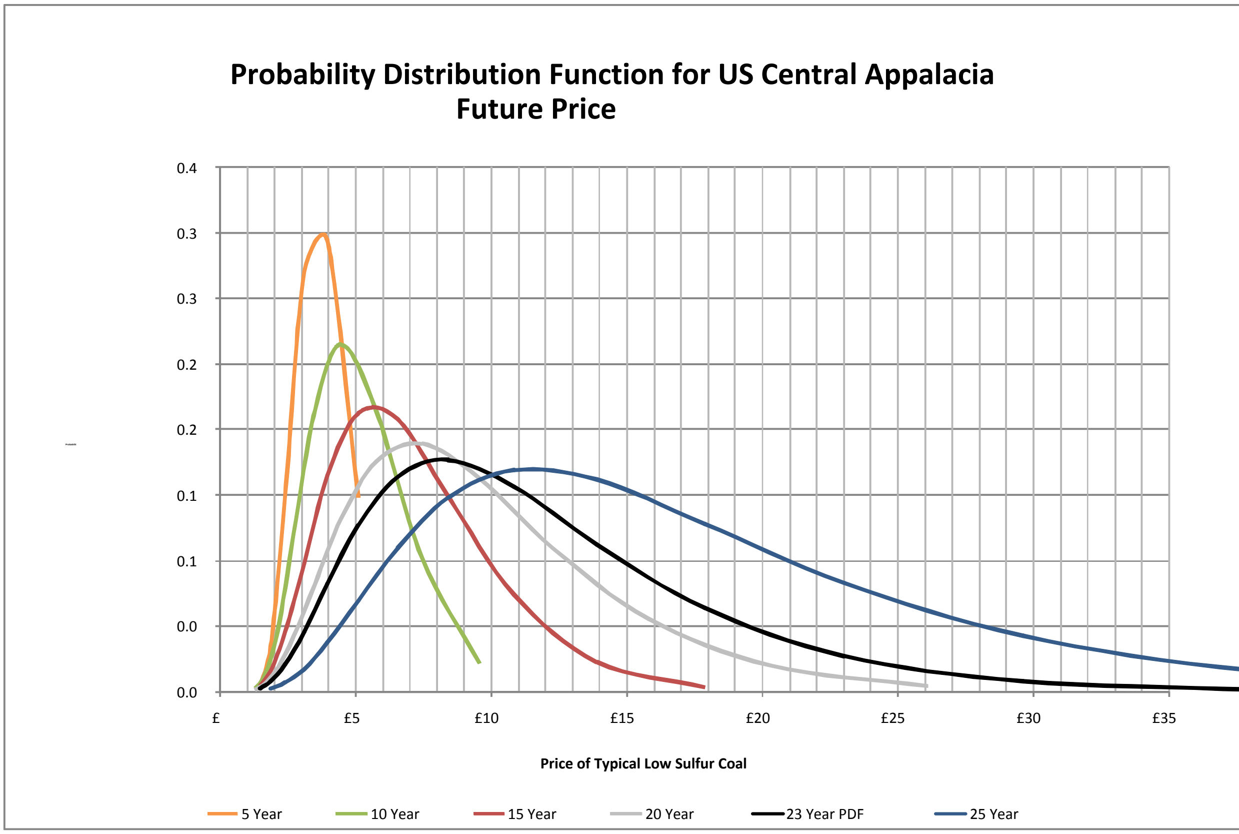



**Figure 16 PDFs for Price of Low Sulfur Carbon**

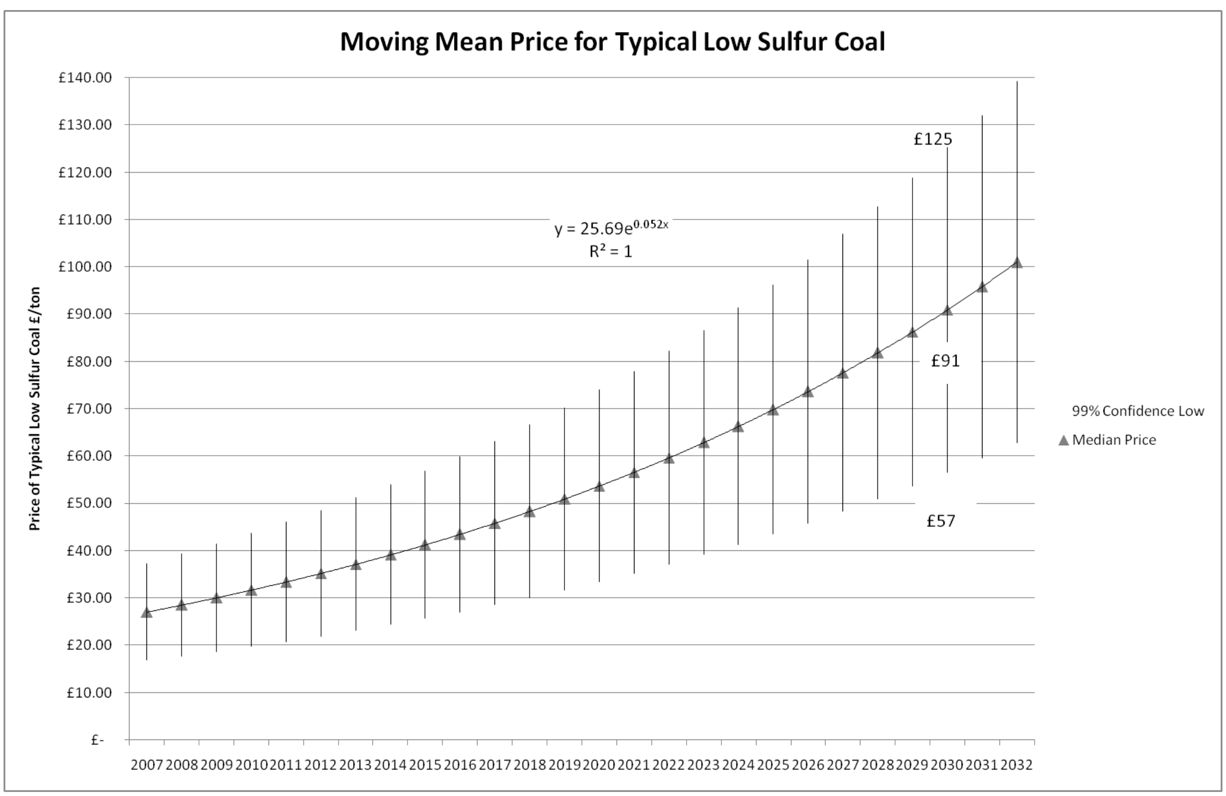



**Figure 17 Low Sulfur Coal 25 Years of Mean Prices**

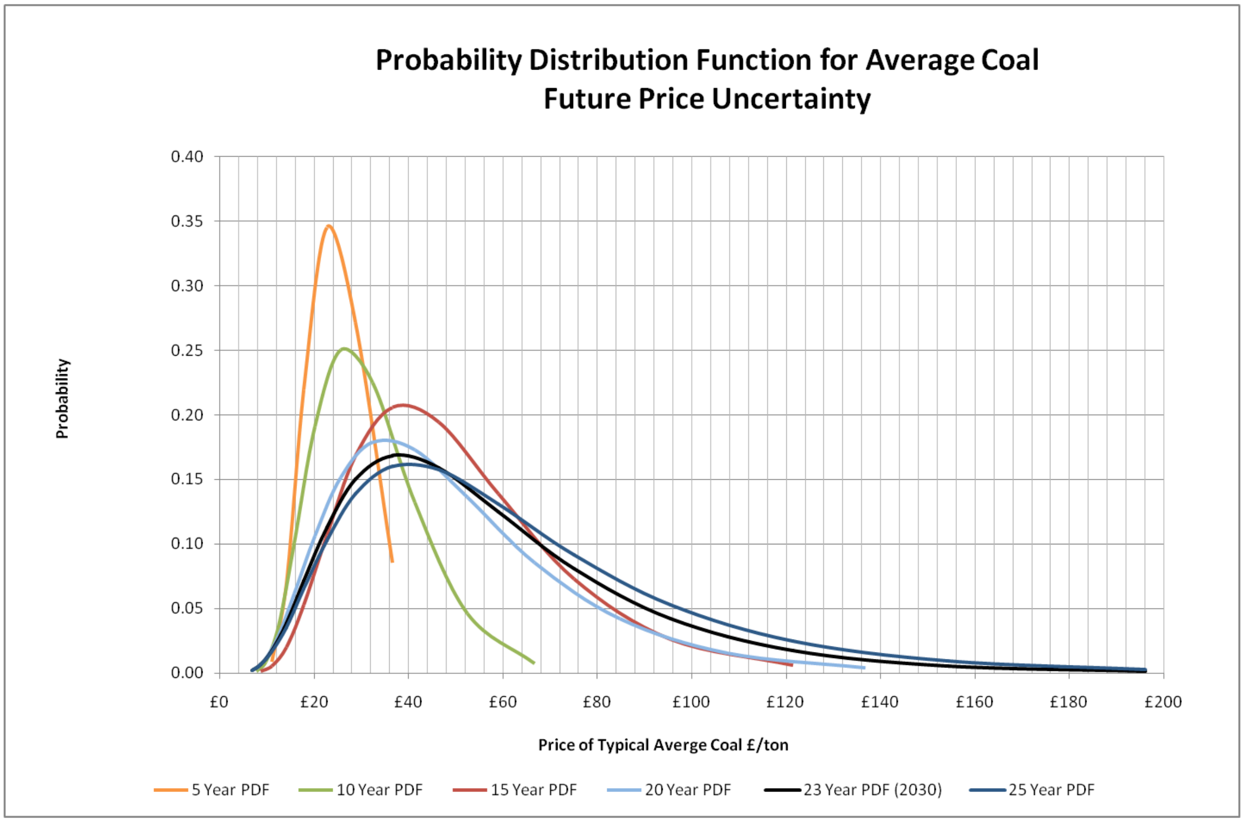



**Figure 19 PDFs for Price of Medium Sulfur Carbon**

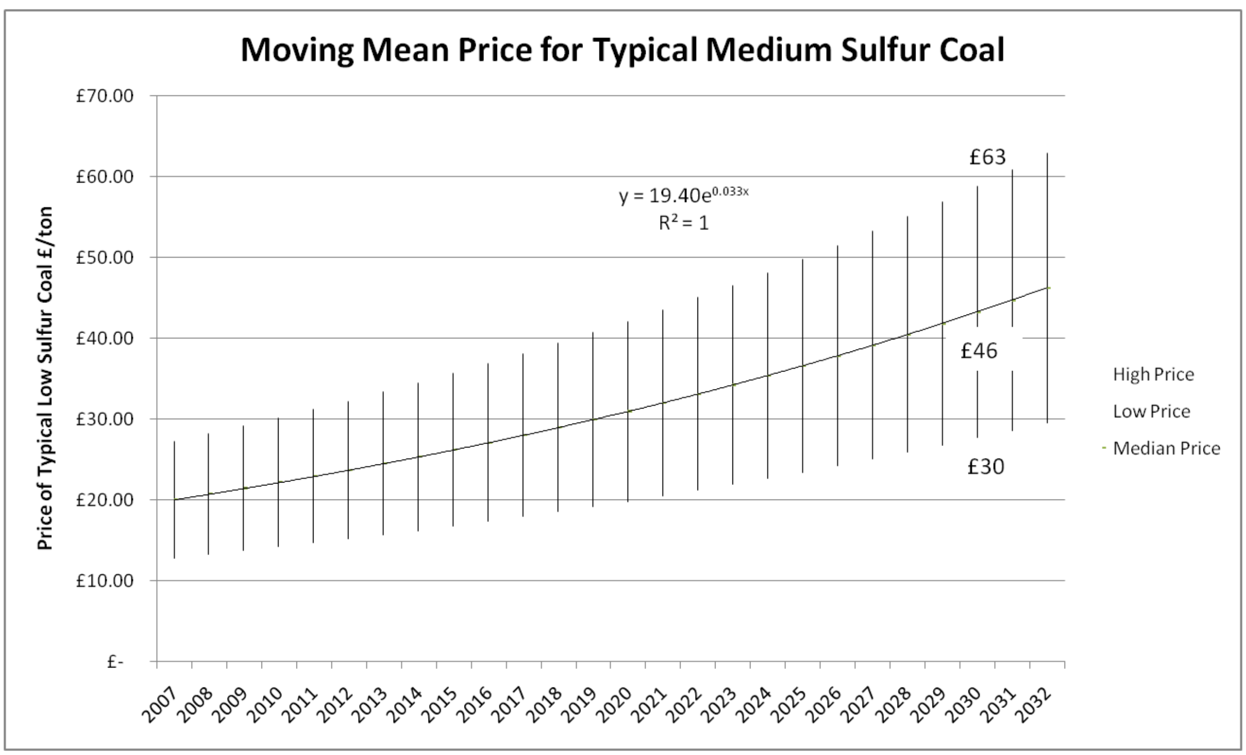



**Figure 18 Medium Sulfur Coal 25 Years of Mean Prices**

## 4.5 Cost of Electricity for Five Scenarios

After determining coal and carbon low, mean, and maximum prices, the next step is to analyze existing UK power plants based on the five scenarios to determine electricity-generating costs per kilowatt-hour (£/kWh). The Carnegie Mellon University Integrated Environmental Control Model (IECM) was used to analyze typical pulverized coal plants and to calculate performance and costs.

### *4.5.1 IECM Interface*

The IECM interface was applied to quickly develop and compare scenarios. It is not meant to calculate exact costs that would be incurred by each individual plant; actual costs will vary somewhat based on individual plant characteristics. One of the ICEM functions is modeling coal-fired power plants to determine the financial and operating impacts of implementing post-combustion $CO_2$ Amine CCS. The model also allows for numerous retrofit technologies for SOx, NOx, and particulate control (see **Error! Reference source not found.**), which can be used for all five scenarios described below.

Plant level investment decisions in plant configuration, including FGD and CCS retrofit, are considered small because they are levelized throughout the life of the component. This means payback assessments are limited because they fail to consider market volatility. Therefore, the analysis considered volatility through low, median, and high coal and carbon prices, and applied a conservative discount rate due to the complexity of each project. In addition, experience shows that construction capital costs are largely uncertain and frequently grossly underestimated. The model defaults are constant 2005 dollars with zero inflation and a discount rate of 10.3 percent. This rate is in-line with other UK power plant cost estimations (MottMacDonald, 2004). Volatility and interest (inflation) have been accounted for in the real options price calculations of coal and carbon.

### *4.5.2 Scenario Modeling*

The five scenarios, described in

Table 6, were analyzed using the IECM interface for low, mean, and high year 2030 coal and carbon dioxide prices. Since Scenario 1 assumes no FGD-retrofit, the low sulfur coal PDF was used, while the other four scenarios used the medium sulfur coal PDF. All plants were modeled with existing cold-side ESP for particulate control, necessary to meet current particulate matter standards. If the plant has opted into the LCPD, to be conservative, the model assumed that the capital investment costs have already been paid-off and only summed levelized retrofit and plant operating costs over a 30-year life. If the plant opts out, as in Scenarios 4 and 5, new supercritical 50-year plants, sized 500, 800, and 1000 MW, with and without CCS, were modeled to understand the performance differences between the current UK new plant proposals.

**Table 6 Scenario Plant Input Characteristics**

| | Description | NOx Control | SO2 Control | Mercury | CO2 CCS | Boiler Type/ Efficiency |
|---|---|---|---|---|---|---|
| **Scenario 1** | No FGD<br>No CCS<br>Low Sulfur | None | None | None | None | Sub-critical<br>36% |
| **Scenario 2** | FGD<br>No CCS<br>Med Sulfur | In-furnace controls<br>Hot-side SCR | Wet FGD | Carbon Injection | None | Sub-critical<br>35% |
| **Scenario 3** | FGD<br>CCS<br>Med Sulfur | In-furnace controls<br>Hot-side SCR | Wet FGD | Carbon Injection | Amine System | Sub-critical<br>26% |
| **Scenario 4** (500, 800, 1000 MW) | New Plant<br><br>FGD/ No CCS<br>Med Sulfur | In-furnace controls<br>Hot-side SCR | Wet FGD | Carbon Injection | None | Super-critical<br>43% |
| **Scenario 5** (500, 800 1000 MW) | New Plant<br>FGD/CCS<br>Med Sulfur | In-furnace controls<br>Hot-side SCR | Wet FGD | Carbon Injection | Amine System | Super-critical<br>34% |

The IECM interface returns various plant, fuel, plant component, pollutant, and financial results. Each IECM model run was entered into spreadsheets to analyze the economic, environmental, and performance considerations of each plant configuration scenario. Example IECM model input and output screens are shown in Appendix B, while example spreadsheet calculations are shown in Appendix C. The spreadsheets enabled calculation of the cost of electricity (COE) per kWh, graphing and comparing results, and further analysis of similarities and differences between the scenarios. Specific model outputs used in the calculations include: capital and revenue required for the base plant, plant technology components, emissions taxes, fixed and variable operating and maintenance (O&M), major flue gas components, annual power generation, plant efficiency, and net electrical output. The model outputs were converted to annual levelized and total O&M costs per kWh to determine total cost of electricity generation.

### *4.5.3 Modeling Results*

To derive the following modeling results, Appendix C tables illustrate the transition of IECM iteration outputs into UK coal station inputs. A random iteration of Scenario 4, using low coal and mean carbon dioxide prices, demonstrates the process. Table 7 depicts the overall coal plant modeling results for all five scenarios for 2030 mean coal and carbon prices. It shows the plant parameters, including net output, heat rate, annual power generation, and plant efficiency. A general and expected pattern emerged that plant efficiency decreases with increased retrofits on an existing plant or with pollution technology on a new plant due to operating energy requirements. FGD technology decreases plant efficiency by less than one percent, but CCS decreases efficiency by approximately 10 percent. The IECM iterations also find that FGD installation reduces $SO_2$ by 99.95 percent and $SO_3$ (sulfuric acid) by 99.5 percent in existing and new plants, and that CCS reduces $CO_2$ by almost 90 percent. The results also indicate that without CCS technology, one existing 500 MW plant emits over 2.6 $MtCO_2$ per year, while one new supercritical plant emits over 2.2 $MtCO_2$ per year.

Figure 20 graphs the 2030 $CO_2$ and $SO_2$ emissions/MW results from Table 7. The left-hand axis represents carbon dioxide emissions, while the right-hand axis represents sulfur dioxide emissions, with both variables following the same general pattern for each scenario. For instance, Scenarios 3 and 5, with CCS, fall in the bottom left quadrant of the graph, exhibiting both low electricity costs and low emissions rates. On the opposite upper right quadrant, Scenarios 1, 2, and 4, without CCS exhibit both high electricity costs and high emissions rates.

## Table 7 2030 Coal Plant Modeling Results and Calculations

**2030 Coal Plant Modeling Results and Calculations (All plants are assumed to operate for 6,575 hours/year)**

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 4 | Scenario 4 | Scenario 5 | Scenario 5 | Scenario 5 |
|---|---|---|---|---|---|---|---|---|---|
| | Retrofit<br>No FGD<br>No CCS<br>Low Sulfur | Retrofit<br>FGD<br>No CCS<br>Med Sulfur | Retrofit<br>FGD<br>CCS<br>Med Sulfur | New 500 MW<br>Supercritical<br>FGD<br>No CCS<br>Med Sulfur | New 800 MW<br>Supercritical<br>FGD<br>No CCS<br>Med Sulfur | New 1000 MW<br>Supercritical<br>FGD<br>No CCS<br>Med Sulfur | 500 MW<br>Supercritcal<br>FGD<br>CCS<br>Med Sulfur | 800 MW<br>Supercritcal<br>FGD<br>CCS<br>Med Sulfur | New 1000 MW<br>Supercritcal<br>FGD<br>CCS<br>Med Sulfur |
| **Plant Parameters** | | | | | | | | | |
| Net Electrical Output | 469.7 | 457.7 | 333.1 | 459.8 | 736.3 | 920.6 | 357.7 | 572.9 | 716.3 |
| Net Plant Heat Rate, HHV (Btu/kWh) | 9,381 | 9,655 | 13,270 | 7876 | 7869 | 7867 | 10,130 | 10,110 | 10,110 |
| Annual Operating Hours | 6,575 | 6,575 | 6,575 | 6575 | 6575 | 6575 | 6575 | 6575 | 6575 |
| Annual Power Generation (BkWh/yr) | 3.088 | 3.009 | 2.19 | 3.023 | 4.841 | 6.053 | 2.352 | 3.766 | 4.71 |
| Net Plant Efficiency, HHV (%) | 36.4% | 35.3% | 25.7% | 43.3% | 43.4% | 43.37% | 33.7% | 33.7% | 33.8% |
| **Plant Energy Requirements** | 30.34 | 42.29 | 166.92 | 40.17 | 63.71 | 20.89 | 142.33 | 227.14 | 283.70 |
| Gross Electrical Output (MW) | 500 | 500 | 500 | 500 | 800 | 58.5 | 500 | 800 | 1000 |
| Boiler Use (MW) | 29.25 | 29.25 | 29.25 | 29.25 | 46.80 | 0.05 | 29.25 | 46.80 | 58.50 |
| In-furnace NOx Use (MW) | 0 | 0.050 | 0.050 | 0.050 | 0.050 | 4.326 | 0.050 | 0.050 | 0.05 |
| Hot-Side SCR Use (MW) | 0 | 2.63 | 2.63 | 2.16 | 3.46 | 0.9125 | 2.16 | 3.46 | 4.33 |
| Cold-Side ESP Use (MW) | 1.09 | 0.91 | 0.91 | 0.91 | 0.91 | 15.51 | 0.91 | 0.91 | 0.91 |
| Wet FGD Use (MW) | 0 | 9.40 | 13.92 | 7.75 | 12.41 | 0.09508 | 11.46 | 18.34 | 22.92 |
| Activated Carbon Inj. Use (MW) | 0.000 | 0.058 | 0.058 | 0.048 | 0.076 | 0 | 0.048 | 0.076 | 0.10 |
| Amine Scrubber Use (MW) | 0 | 0.00 | 120.10 | 0 | 0 | 0 | 98.45 | 157.50 | 196.90 |
| **Major Flue Gas Components (tonnes/yr)** | | | | | | | | | |
| Nitrogen (N2) | 10,140,056 | 10,474,081 | 10,474,083 | 8,583,259 | 13,730,828 | 17,166,518 | 8,583,260 | 13,730,831 | 17,166,521 |
| Oxygen (O2) | 867,273 | 889,939 | 888,746 | 729,488 | 1,167,299 | 1,458,975 | 728,295 | 1,164,914 | 1,456,589 |
| Water Vapor (H2O) | 710,997 | 1,594,971 | 1,594,971 | 1,306,874 | 2,094,220 | 2,620,310 | 1,306,874 | 2,094,220 | 2,620,310 |
| **Carbon Dioxide (CO2)** | **2,641,186** | **2,711,570** | **271,634** | **2,222,462** | **3,555,581** | 4,443,730 | **222,664** | **356,155** | **445,208** |
| Carbon Monoxide (CO) | - | - | - | - | - | - | - | - | - |
| Hydrochloric Acid (HCl) | 724 | 61.32 | 3.07 | 50.26 | 80 | 101 | 2.51 | 4.02 | 5 |
| **Sulfur Dioxide (SO2)** | **12,425** | **7,867** | **4.07** | **6,448** | **10,313** | 12,890 | **3.33** | **5.33** | **7** |
| Sulfuric Acid (equivalent SO3) | 46.97 | 131 | 0.66 | 108 | 174 | 220 | 0.54 | 0.87 | 1 |
| Nitric Oxide (NO) | 6,537 | 983 | 983 | 806 | 1,414 | 1,871 | 806 | 1414 | 1,871 |
| Nitrogen Dioxide (NO2) | 527 | 79.33 | 59.49 | 65.02 | 114 | 151 | 48.76 | 85.53 | 113 |
| Ammonia (NH3) | 0.00 | 15.04 | 886 | 12.33 | 20 | 25 | 727 | 1,166 | 1,461 |
| Argon (Ar) | 172,739 | 178,346 | 178,346 | 146,196 | 233,877 | 292,332 | 146,196 | 233,877 | 292,332 |
| **Total Major Flue Gas Components (tonnes/yr)** | **14,552,510** | **15858045** | **13,408,735** | **12,997,166** | **20,793,079** | **25,994,331** | **10,987,050** | **17,584,053** | **21,986,030** |
| **2030 Cost of Electricity ( £/kWh)** | **£ 0.368** | **£ 0.373** | **£ 0.130** | **£ 0.336** | **£ 0.332** | **£ 0.330** | **£ 0.130** | **£ 0.124** | **£ 0.121** |
| **2030 Carbon Dioxide Emissions (tonne/MWh)** | **855.31** | **901.15** | **124.03** | **735.18** | **734.47** | **734.14** | **94.67** | **94.57** | **94.52** |
| **2030 SO2 Emissions (tonne/MWh)** | **4.023** | **2.615** | **0.002** | **2.133** | **2.130** | **2.129** | **0.001** | **0.001** | **0.001** |

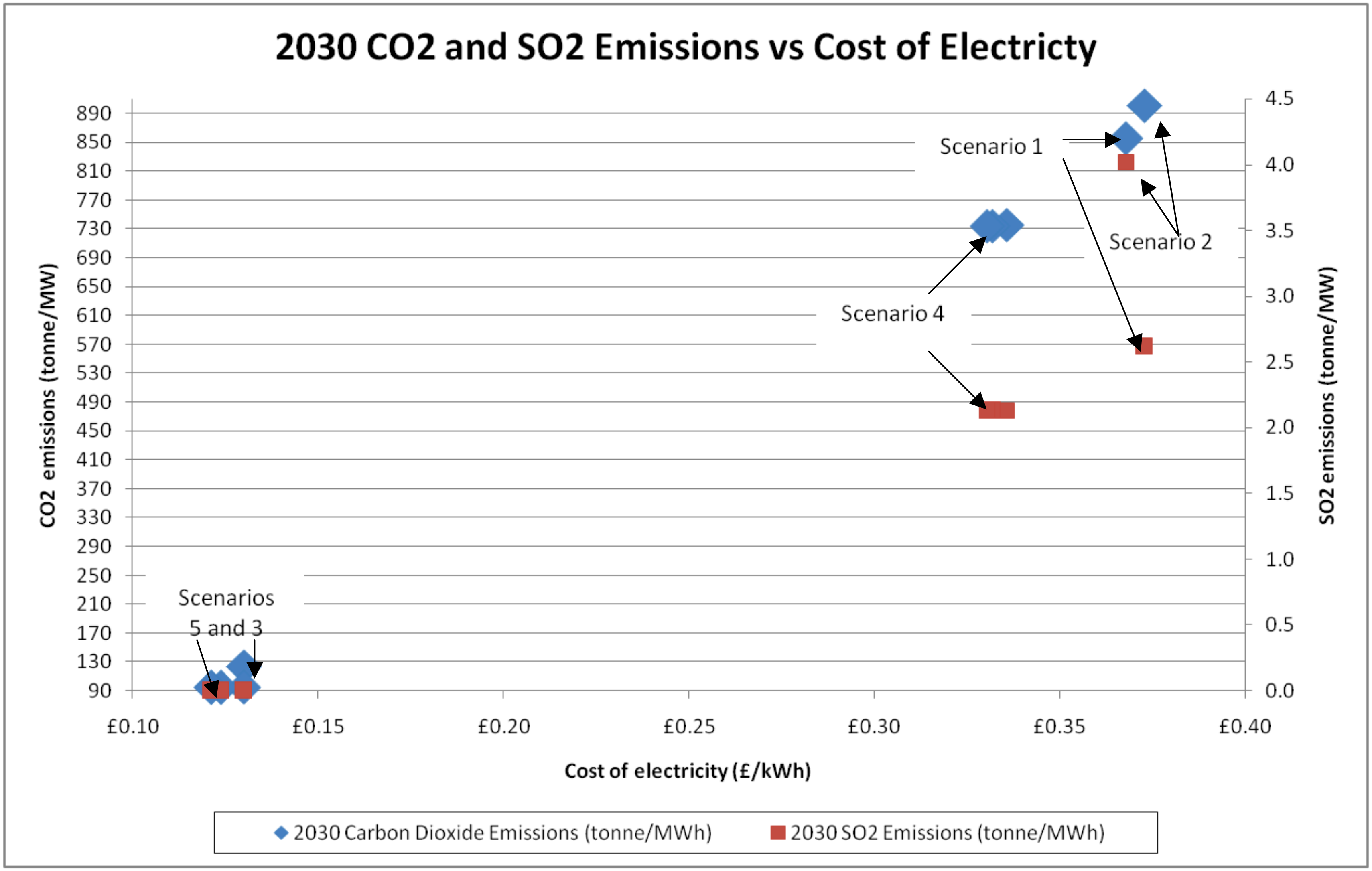



**Figure 20 Relative Emissions and COE of the five Scenarios**

Figure 21 and Figure 22 contain electricity-generating cost versus carbon dioxide price and electricity-generating cost versus coal price. They represent several of the analysis modeling iterations. In the UK, 500 MW is the most popular plant size, and was chosen to illustrate graphically the differences in Scenario outcomes. Figure 21 shows 2030 electricity-generating costs using mean low and medium sulfur coal prices, and varying low, mean, and high carbon prices. Figure 22 shows 2030 electricity-generating costs using mean carbon prices versus low, mean, and high coal prices. The numeric results are also summarized in Table 8.

**Table 8 Electricity Generating Price by Carbon and Coal Prices**

| 500 MW Plant Electricity Cost (£/kWh) | | | | | 2030 Carbon Price (£/tonne) Low £ 22.72 | Mean £ 156.67 | High £ 290.63 |
|---|---|---|---|---|---|---|---|
| **Scenario 1** | **Low Sulfur Price (£/tonne)** | **Retrofit No FGD No CCS** | Low | £ 56.60 | £ 0.08 | £ 0.09 | £ 0.10 |
| | | | Mean | £ 90.95 | £ 0.36 | £ 0.37 | £ 0.38 |
| | | | High | £ 125.29 | £ 0.65 | £ 0.65 | £ 0.66 |
| **Scenario 2** | **Medium Sulfur Price (£/tonne)** | **Retrofit FGD No CCS** | Low | £ 27.69 | £ 0.07 | £ 0.37 | £ 0.66 |
| | | | Mean | £ 43.26 | £ 0.08 | £ 0.37 | £ 0.67 |
| | | | High | £ 58.83 | £ 0.09 | £ 0.38 | £ 0.67 |
| **Scenario 3** | | **Retrofit FGD + CCS** | Low | £ 27.69 | £ 0.08 | £ 0.12 | £ 0.16 |
| | | | Mean | £ 43.26 | £ 0.09 | £ 0.13 | £ 0.17 |
| | | | High | £ 58.83 | £ 0.10 | £ 0.14 | £ 0.18 |
| **Scenario 4** | | **New FGD No CCS** | Low | £ 27.69 | | £ 0.33 | |
| | | | Mean | £ 43.26 | £ 0.10 | £ 0.34 | £ 0.58 |
| | | | High | £ 58.83 | | £ 0.35 | |
| **Scenario 5** | | **New FGD + CCS** | Low | £ 27.69 | | £ 0.12 | |
| | | | Mean | £ 43.26 | £ 0.10 | £ 0.13 | £ 0.16 |
| | | | High | £ 58.83 | | £ 0.14 | |

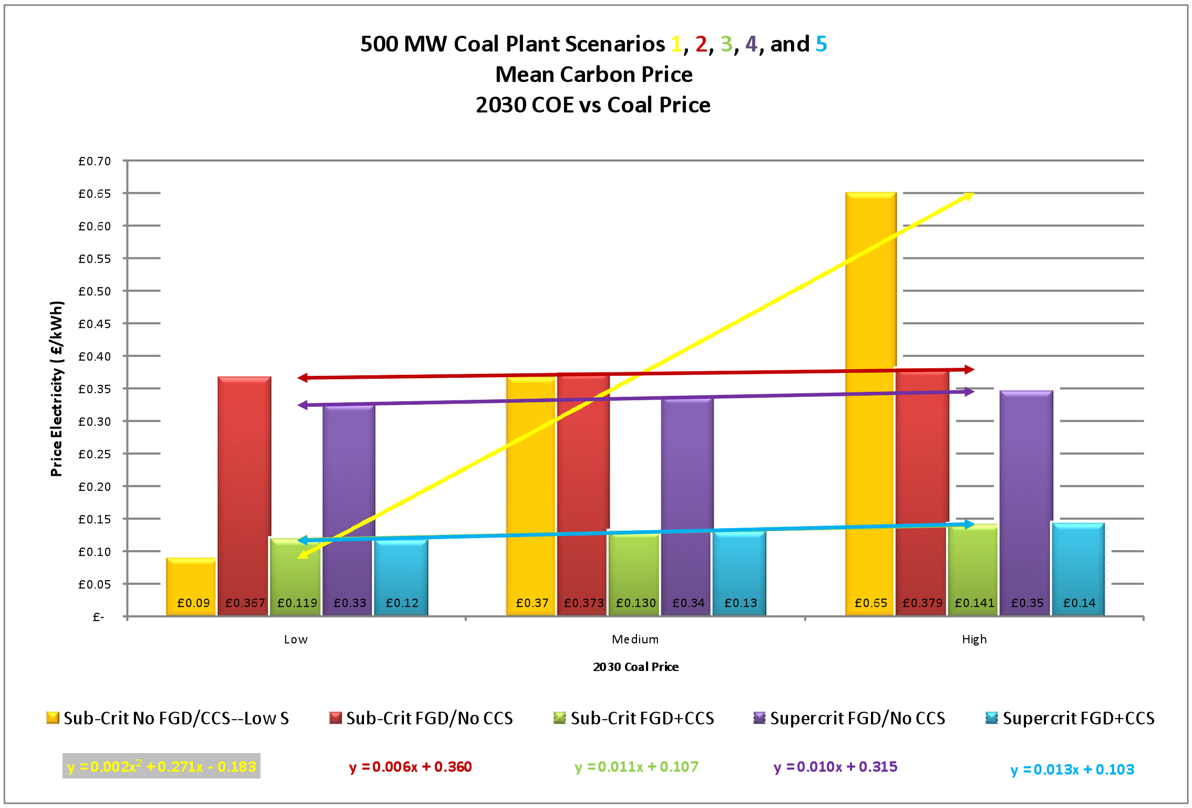



**Figure 21 Coal Price Uncertainty Effect on COE (Mean Carbon Price)**

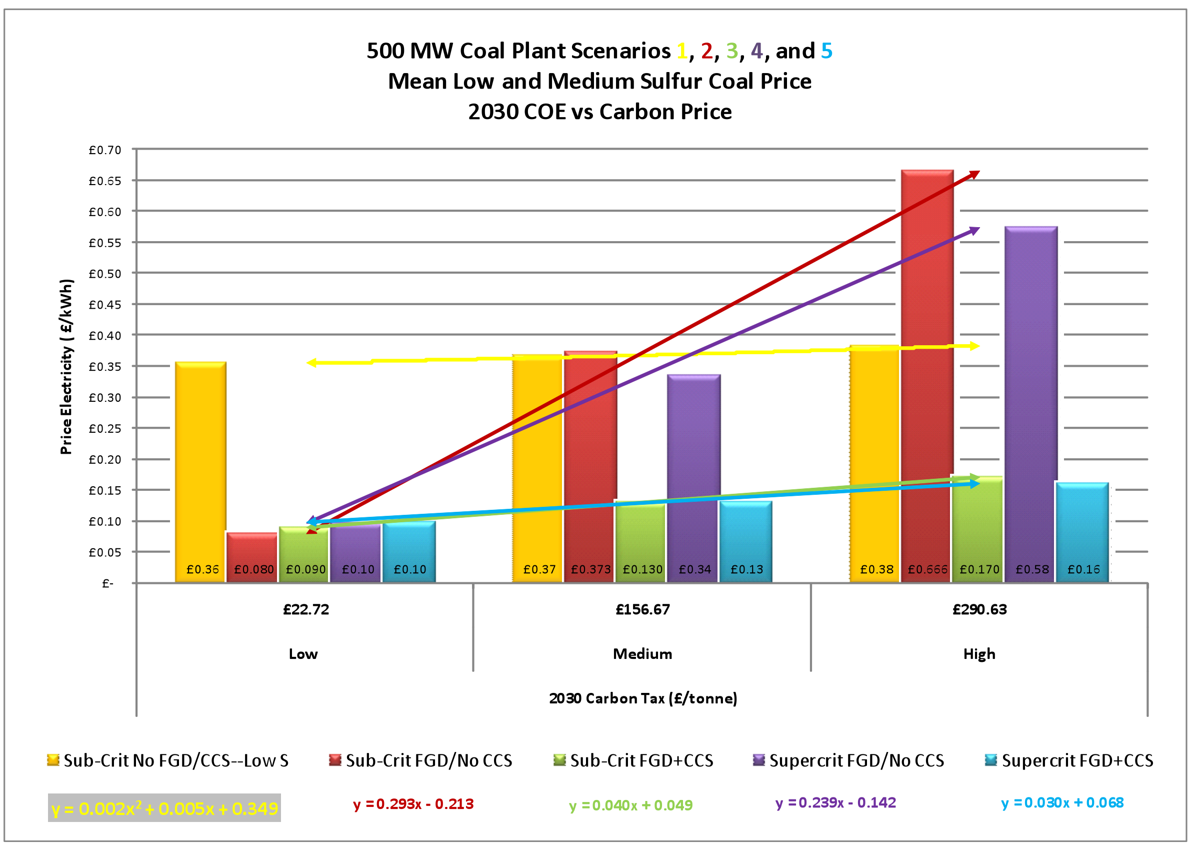



**Figure 22 Carbon Price Uncertainty Effect on COE (Mean Coal Price)**

Figure 21 and Figure 22 were analyzed to determine how scenarios react to coal and carbon price uncertainties (low, mean, and high prices). For purposes of distinguishing between scenario sensitivities, electricity-generation costs are categorized as follows:

> £0.45/kWh = very high
£0.30/kWh to £0.45/kWh = high
£0.15/kWh to £0.30/kWh = medium
< £0.15/kWh = low

Table 9 compiles the price sensitivity and pollution results for a typical 500 MW plant. Scenarios 2, and 4 (no CCS) show very high sensitivity to carbon prices; Scenario 1 (low sulfur coal) has high costs under all carbon prices; and Scenarios 3 and 5 (CCS) show low to medium cost sensitivity with costs at low to just at medium electricity-generation costs. Scenario 1 (low sulfur coal) shows high sensitivity to coal price with low to very high electricity-generation costs; Scenarios 2 and 4 (no CCS) have high costs across all medium sulfur coal prices; and Scenarios 3 and 5 (CCS) have low electricity generation costs across all medium sulfur coal prices.

**Table 9 Scenario Price Sensitivity and Pollution per Year Characteristics**

| | | Electricity Generation Cost Sensitivity | | Pollution/Year | | |
|---|---|---|---|---|---|---|
| **Scenario** | **Description** | **Carbon Price** | **Coal Price** | **Mtonne $CO_2$** | **Tonne $SO_2$** | **Comment** |
| 1 | Low Sulfur, No Retrofit | High cost all scenarios, low sensitivity | High sensitivity, low to high cost | 2.64 | 12.4 | Likely does not meet regulations. Needs even less sulfur in coal = very low sulfur coal (from Indonesia). |
| 2 | FGD Retrofit | Very high sensitivity, low to very high cost | High cost all scenarios | 2.71 | 7.87 | Meets 2008 regulation. Likely will not meet future regulations. |
| 3 | FGD/CCS Retrofit | Medium sensitivity, low to medium cost | Low cost all scenarios | 0.27 | 4.07 | Exceeds 2008 regulation. Should meet future regulations. |
| 4 | FGD New Supercritical | Very high sensitivity, low to very high cost | High cost all scenarios | 2.22 | 6.45 | Meets 2008 regulation. Likely will not meet future regulations. |
| 5 | FGD/CCS New Supercritical | Medium sensitivity, low to medium cost | Low cost all scenarios | 0.22 | 3.33 | Exceeds 2008 regulation. Should meet future regulations. |

The scenario results show that, in current times of relatively low coal and carbon prices, plants can be run economically without CCS. However, without CCS and when 2030 coal and carbon prices are modeled, electricity-generating costs either become very volatile or are simply high. In addition, retrofitting existing plants (even assuming the original capital costs are paid off) is almost as expensive to generate electricity (and in high price scenarios slightly more expensive) than a new plant. This indicates that power plant owners should carefully consider whether FGD retrofit is cost effective for their plant.

The scenario results were applied to the UK power plant system with results shown in Table 10 and Table 11. Table 10 compares existing power plants in the year 2030 for FGD retrofit (to meet LCPD standards) and FGD/CCS retrofit scenarios. The purpose of the analysis was to determine mean price scenario 2030 estimates of cost of electricity (COE) and emissions levels. As of January 2007, 8,180 MW have opted out and plan to close by 2016, while the other 20,684 MW have opted in and have either: (1) retrofit with FGD, or (2) plan to retrofit with FGD (JESS, 2006). Table 12 provides the DTI $CO_2$ emissions assumptions for several plant types. This table was included or a check on IECM program outputs for pollution.

Table 10 includes the existing plant retrofit scenarios' total capital costs that ranged from £1,514 (compared to industry estimates of about £950) for Scenarios 2 and 4 (FGD-only) to £4,358 for Scenarios 3 and 5 (FGD/CCS). The average COE of £0.383 for Scenarios 2 and 4 (FGD-only) is 2.7 times higher than the Scenario 3 and 5 (FGD and CCS) average COE of £0.141—even considering new plants in Scenario 5. For comparison of data in Tables 10 and 12, UK 2030 carbon dioxide emissions goals are 330 $MtCO_2$ per year. In Scenarios 2 and 4 (FGD-only) the UK coal power plant system would emit over 35% of that goal, while Scenarios 3 and 5 would emit less than 4%.

Table 11 includes the new plant system total capital costs which range from £2,904 (compared to industry estimates of about £2,180) for Scenarios 2 and 4 (FGD-only) to £8,092 for Scenarios 3 and 5 (FGD/CCS). With the new plants, the average COE of £0.374 for Scenarios 2 and 4 (FGD-only) is 2.65 times higher than the Scenario 3 and 5 (FGD and CCS) average COE of £0.141. For comparison of emissions data in Table 11 and 12, in Scenarios 2 and 4 (FGD-only), the UK coal power plant system would emit almost 40% of the UK $CO_2$ goal, while Scenarios 3 and 5 would emit around 4%.

It is important to note that industry cost estimates are significantly lower than IECM model outputs in both existing and proposed plant configurations. Some of this difference may be due to conversion between dollars and pounds in the analysis (using January 2007 conversions of \$1 = £0.52). In addition, the source data should be updated to reflect current and future prices. Despite these limitations, plant owners should carefully consider retrofit and new plant costs when developing investment strategies. A real options approach will provide flexibility as well as an eye to what the future could be. The same analysis can be applied to other sustainable energy technologies to compare risks and possible outcomes. Specifically, some plant owners that have opted-in and plan to FGD-retrofit the plant, especially with the likely possibility of later retrofitting with CCS technology, would incur more costs than the current industry estimates indicate. All plant owners should reconsider investments and apply a strategy of investment decision-making that considers dynamic conditions and systems analysis.

**Table 10 UK Existing Power Plant Year 2030 COE and Emissions** (Jess, 2006)
FGD-retrofit and FGD/CCS-retrofit Scenarios

| UK Coal Existing Stations and Future FGD and/or CCS Retrofit Costs | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Status as of January 2007 | | | | | FGD Retrofit only | | | | | FGD and CCS Retrofit | | | |
| Installation | Installed Capacity (MW) | # of boilers | Cap/ boiler (MW) | FGD Opted-in (MW) | FGD Status as of January 2007 | 2030 Estimated COE (£/kWh) | 2030 Estimated $CO_2$ Emissions (tonnes/yr) | 2030 Estimated $SO_2$ Emissions (tonnes/yr) | IECM Modeling FGD Retrofit Costs (£m) | Estimated Industry FGD Costs (£m) | 2030 Estimated COE (£/kWh) | 2030 Estimated $CO_2$ Emissions (tonnes/yr) | 2030 Estimated $SO_2$ Emissions (tonnes/yr) | IECM Modeling CCS Retrofit Costs (£m) |
| Aberthaw | 1,500 | 3 | 500 | 1500 | Fit by 2008 | £ 0.373 | 8,134,711 | 23,602 | £ 197 | £ 153 | £ 0.130 | 814,903 | 12.20 | £ 317 |
| Cottam | 2,000 | 4 | 500 | 2000 | Fit by 2007 | £ 0.373 | 10,846,281 | 31,470 | £ 263 | | £ 0.130 | 1,086,537 | 16.27 | £ 423 |
| Drax | 3,960 | 6 | 660 | 3960 | Fit | £ 0.405 | 21,476,638 | 62,343 | N/A | | £ 0.160 | 2,151,601 | 32.26 | £ 564 |
| Eggborough | 2,000 | 4 | 500 | 2000 | 1/2 Units fit | £ 0.373 | 10,846,281 | 31,470 | £ 132 | £ 100 | £ 0.130 | 1,086,537 | 16.27 | £ 423 |
| Ferrybridge | 2,000 | 4 | 500 | 1,000 | 1/2 Units 2008 | £ 0.373 | 10,846,281 | 31,470 | £ 132 | £ 113 | £ 0.130 | 1,086,537 | 16.27 | £ 423 |
| Fiddlers | 2,000 | 4 | 500 | 2000 | Fit by 2008 | £ 0.373 | 10,846,281 | 31,470 | £ 263 | £ 113 | £ 0.130 | 1,086,537 | 16.27 | £ 423 |
| Kilroot | 500 | 1 | 500 | 520 | Fit by 2007 | £ 0.373 | 2,711,570 | 7,867 | £ 66 | £ 35 | £ 0.130 | 271,634 | 4.07 | £ 106 |
| Longannet | 2,304 | 4 | 576 | 2304 | Fit by 2008 | £ 0.406 | 12,473,461 | 36,194 | £ 330 | £ 170 | £ 0.163 | 1,249,732 | 18.74 | £ 514 |
| Ratcliffe | 2,000 | 4 | 500 | 2000 | Fit | £ 0.373 | 10,846,281 | 31,470 | N/A | | £ 0.130 | 1,086,537 | 16.27 | £ 423 |
| Rugeley | 1,000 | 2 | 500 | 1000 | Will fit | £ 0.373 | 5,423,140 | 15,735 | £ 132 | £ 100 | £ 0.130 | 543,268 | 8.14 | £ 212 |
| Uskmouth | 400 | 3 | 133.33 | 400 | Fit | £ 0.429 | 2,165,200 | 6,284 | N/A | | £ 0.202 | 216,878 | 3.25 | £ 106 |
| West Burton | 2,000 | 4 | 500 | 2000 | Fit | £ 0.373 | 10,846,281 | 31,470 | N/A | | £ 0.130 | 1,086,537 | 16.27 | £ 423 |
| Cockenzie | 1,200 | 2 | 600 | 0 | Opt-out | N/A | N/A | N/A | | | N/A | N/A | N/A | |
| Didcot | 2,000 | 6 | 333.33 | 0 | Opt-out | N/A | N/A | N/A | | | N/A | N/A | N/A | |
| Ironbridge | 1,000 | 2 | 500 | 0 | Opt-out | N/A | N/A | N/A | | | N/A | N/A | N/A | |
| Kingsnorth | 2,000 | 4 | 500 | 0 | Opt-out | N/A | N/A | N/A | | | N/A | N/A | N/A | |
| Tilbury | 1,000 | 3 | 333.33 | 0 | Opt-out | N/A | N/A | N/A | | | N/A | N/A | N/A | |
| **Total** | **28,864** | **60** | | **20,684** | **Opt-out 8180 MW** | **£ 0.383 Average** | **117,462,405 Total** | **340,847 Total** | **£ 1,514** | **£ 783** | **£ 0.141 Average** | **11,767,238 Total** | **176 Total** | **£ 4,358** |
| Source: | | | | | | | | | | | | | | |

All IECM results and supporting calculations are for 2030 mean coal and mean carbon prices as determined by the lattice analysis.

**Table 11 UK Existing and Proposed Power Plant Year 2030 COE and Emissions** (Jess, 2006)
FGD and FGD/CCS Scenarios

| UK Coal Proposed Stations and Future FGD and/or CCS Costs | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Status as of January 2007 | | | | | New Plant FGD only | | | | | New Plant FGD and CCS | | | | |
| Installation | Installed Capacity (MW) | # of boilers | Cap/ boiler (MW) | FGD Opted-in (MW) | FGD Status as of January 2007 | 2030 Estimated COE ( £/kWh) | 2030 Estimated CO2 Emissions (tonnes/yr) | 2030 Estimated SO2 Emissions (tonnes/yr) | IECM Modeling New FGD Plant FGD Costs | Estimated Industry Costs ( £m) | 2030 Estimated COE (£/kWh) | 2030 Estimated CO2 Emissions (tonnes/yr) | 2030 Estimated SO2 Emissions (tonnes/yr) | IECM Modeling CCS Retrofit Costs ( £m) | Estimated Industry Costs ( £m) |
| Ferrybridge (New) | 500 | 1 | 500 | 500 | FGD w/CCS? | £ 0.336 | 2,222,462 | 6,448 | £ 359 | £ 250 | £ 0.130 | 222,664 | 3.33 | £ 453 | £ 350 |
| Killingholme/Humberside (New) | 450 | 1 | 450 | 450 | FGD & CCS | | | | | | £ 0.149 | 220,278 | 3.30 | £ 434 | £ 1,000 |
| Kingsnorth (new) | 1,600 | 2 | 800 | 1,600 | FGD w/CCS? | £ 0.332 | 7,111,161 | 20,626 | £ 1,031 | £ 1,000 | £ 0.124 | 712,309 | 20,626.07 | £ 1,317 | |
| Hatfield (New) | 900 | 1 | 900 | 900 | FGD & CCS | | | | | | £ 0.139 | 440,436 | 6.60 | £ 748 | £ 800 |
| Tilbury (New) | 1,000 | 1 | 1000 | 1,000 | FGD & CCS | | | | | | £ 0.121 | 445,208 | 6.67 | £ 782 | £ 800 |
| **Total Existing + New** | **4,450** | | | | | **£ 0.374** | **126,796,028** | **367,921** | **£ 2,904** | **£ 2,033** | **£ 0.141** | **13,808,134** | **20,822** | **£ 8,092** | |
| **Total New Only** | **Total** | | | | | **Average** | **Total** | **Total** | | | **Average** | **Total** | **Total** | **£ 3,735** | **£ 2,950** |

All IECM results and supporting calculations are for 2030 mean coal and mean carbon prices as determined by the lattice analysis.

**Table 12 DTI $CO_2$ Emissions Assumptions**

| Typical 500 MW Electricity Generation Plant Yearly Emissions | | |
|---|---|---|
| **Plant Type** | **Carbon Emissions (Mtonnes/yr)** | **$CO_2$ Emissions (Mtonnes/yr)** |
| Conventional Coal | 0.9 | 3.300 |
| Efficient Coal | 0.715 | 2.622 |
| Efficient Coal w/ Biomass | 0.625 | 2.292 |
| Efficient Coal w/ CCS | 0.1 | 0.367 |
| Natural Gas | 0.36 | 1.320 |
| Natual Gas w/CCS | 0.1 | 0.367 |
| Source: DTI, 2006 | | |

The analysis considers future carbon and coal prices to determine the best path of investment for coal plant owners, as well as the best policy approach to coal. The findings are clear that without future CCS technology, coal energy production alone would generate over 1/3 of UK target $CO_2$ emissions. Consequently, future stringent carbon regulations are likely. It is entirely possible to take this same analysis a step further and determine how much volatility and at what high prices the UK could handle and still have space for coal generation with or without CCS. Although it is outside the purview of this analysis, the findings can be used to demonstrate that the UK and the EU have not established enough stringency in carbon emissions policies since they do not force plant owners to address carbon emissions now while they are taking care of sulfur emissions. In addition, the weakness of the carbon policies have been demonstrated by low EU ETS trading prices.

### 4.6 Findings and Recommendations

Based on the preceding analysis, several findings and recommendations can be drawn. The following list develops some of the most important ones for the UK going forward:

1. Clean coal (with CCS) should play a strong role in the UK electricity system; however, its role should be diminished compare to Energy Review findings.

2. Pulverized coal power plants should play a strong role in quickly covering load demands, such as due to peak loads or renewable intermittency.

3. Boiler power plants exhibit economies of scale characteristics where, as the scale of production increases, the production costs per unit decrease. In addition, smaller capital requirements per kW exist as the scale of the production increases. Therefore, a few or several of the proposed supercritical power plant owners should meet to discuss partnership on a larger, cheaper plant with CCS and other state of the art technology. It would be cheaper, emit 90% less carbon pollution, and be a huge image boost for clean coal.

4. The COE for retrofit (assuming original investment paid-off) is either only slightly less than or slightly more than a new plant, depending on the scenario. Therefore, existing power plant owners that have opted-in, and plan to build in stages one (FGD) and two (CCS), should carefully reanalyze their financial options before installing FGD technology to:

    a. Opt-out and build a new supercritical plant (partner as above),

    b. Opt-out and invest in a different sustainable energy solution (community and individual renewable generation and microgeneration), or

    c. Opt-in and save investment costs by upgrading all Best Available Technology options at the same time, including FGD, CCS, SCR, carbon injection, etc. analyzed in this chapter, and co-fired with biomass (or waste), which was not analyzed in this thesis.

5. The DTI and EC should work together to reduce carbon price volatility (and uncertainty) through strong and rising price signals. The recent NAP allocations may be a good start, but constant monitoring and adjusting of the cap would ensure stringencies strong enough to force innovative technology development, and to send strong price signals.

6. The DTI should set strong stringency to support clean coal innovation rather than investing in old technology that will be around for another 30 years. This would include direct clean coal carbon technology and sustainable energy subsidies, R&D support, feed-in tariffs, stricter quota obligations, removing energy innovation barriers, and energy tax exemptions.[1]

7. The UK needs to drop "NEEC" (Not Entailing Excessive Cost) from Best Available Technology standards to force technology innovation and create a dynamic market.

8. A 2005 real options analysis determined the optimal carbon price to induce CCS implementation. Based on the coal price of $35.00 per ton (£16.5 per tonne), although higher than today, a price of $17.50 per ton of $CO_2$ (£8.2 per tonne) would induce carbon technology installation by power plant owners. A higher carbon tax of $25.00 per ton (£11.8 per tonne) of $CO_2$ would induce CCS even if coal costs fall to lows of $19.21 per ton (£9 per tonne) (Donnelly, 2005). Since carbon prices and coal prices are related, and lately have fallen below levels necessary to induce CCS, the EU should seriously reconsider NAPs to induce CCS. Inadequate stringency levels will send the wrong signals and cost operators millions of pounds for technology that will soon be outdated and insufficient.

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[1] For instance, MIT's co-generation plant supported an algae farm that captured carbon and grew biofuel; the same technology is currently being tested in Arizona. Although the information is proprietary, the simple and clean technology is showing early promise. Engineers are working to handle issues of scaling up the technology to handle larger power plants.

9. Clean coal is only one piece of the solution and the UK should consider how some of the planned coal investments can be better spent on renewable and microgeneration technologies.

## 4.7 Conclusions

The modeling efforts used in this chapter are somewhat limited by their simplicity. Accuracy is limited by the assumptions of volatility and standard deviation, which are based on limited data. However, comparing the results and findings with previous DTI and DTI-sponsored studies found that the process and results could be used to develop accurate coal system strategic plans. Despite the simplicity applied here, the binomial lattice analysis has some advantages over past modeling techniques since it considers coal and carbon price uncertainties and probabilities of each possible price in future years. In addition, all simple spreadsheet modeling inputs have been determined by the IECM program. It is difficult to determine how accurate these calculations are since many are automatically calculated by the computer program behind the scenes. For instance, the carbon dioxide emissions are higher than DTI computed values, which means that the DTI may want to reanalyze current calculations in case IECM values are more accurate. Overall, despite the simplicity of the some of the modeling techniques, the results are deemed to be an accurate representation of 2030 COE ranges for the scenarios.

The flexible approach to design is recommended for analyzing physical projects, such as coal power plants, where financial characteristics can be applied to the variables. Valuing the option of closing the plant is also an important tool to determine the negative impacts of uncertainties, such as coal and carbon prices in this case. If the analysis shows negative impacts in the event of extremely high coal prices, it is possible to close the plant and take less loss on the overall plant costs. It is also possible to operate the plant up to the LCPD limitations and invest the capital into substitute sustainable energy projects.

## CHAPTER 5: CONCLUSIONS

The United Kingdom (UK) goal to reduce $CO_2$ emissions to 60 percent below 1990 levels by 2060 is an ambitious goal. It is a finding of this thesis that existing UK energy policies promote incremental steps, which will not create the necessary energy transition. Instead, it will encourage plant owners to retrofit with FGD technology now, and later to deal with the carbon emissions issues. The literature review strongly indicates that current UK energy policy is not strategic and stringent enough to send strong price signals to force technology innovation or to push the necessary changes in the energy system. In addition, current UK energy policies rely heavily on the electricity sector to reduce $CO_2$ emissions. It is a finding of this thesis that UK policy should achieve reductions from every sector, and be broad enough to include energy efficiency and demand response policies. However, given existing policy direction that directs attention at the electricity segment, this thesis focuses on the largest electricity polluter, coal, with some consideration of overall energy systems impacts. The focus is on the immediately pressing issue of UK sustainable coal policy.

Given existing policy direction, this thesis focuses on the largest electricity polluter: coal, with consideration of overall energy systems impacts. The focus is on the immediately pressing issue of UK sustainable coal policy. Coal is a relatively abundant, yet dirty fossil fuel. In the EU, regulation will require desulfurization technology on all existing coal plants by 2016, representing a large capital expenditure. In addition, the 2005 start of the European Union Emissions Trading Scheme assigns a price to carbon, most likely requiring future carbon abatement technologies for coal plants. In fact, several proposed UK coal generators are currently considering Carbon Capture and Sequestration (CCS) technology. For these reasons, the future price of coal generation remains largely unknown. This thesis uses real options analysis to create low, medium, and high coal and carbon prices in the year 2030 to account for identified future uncertainties. These scenarios are compared against current and proposed coal and carbon policies to determine scenario paths, which can be modified as factors change. The UK has a unique opportunity to take advantage of ageing and retiring power plants to transform the existing electricity generation system into a clean, robust, secure, and diverse system.

The most pressing issue for the coal industry is how to invest now (by 2008) to meet future environmental regulations in a cost-efficient manner, while also considering the dynamic and uncertain future of coal. The modeling results show that, in current times of relatively low coal and carbon prices, plants can be run economically without CCS. However, without CCS and when 2030 coal and carbon prices are modeled, electricity-generating costs either become very volatile or are simply high. In addition, retrofitting existing plants (even assuming the original capital costs are paid off) is almost as expensive to generate electricity (and in high price scenarios slightly more expensive) than a new plant. This indicates that power plant owners should carefully consider whether FGD retrofit is cost effective for their plant.

The major conclusion of the analysis is that when accounting for high carbon and fuel price uncertainties, it is cheaper to build a new supercritical plant than to retrofit an existing plant with FGD and/or CCS. This is especially true for older plants and if the

FGD and CCS will be built in stages. In addition, although not analyzed in this thesis, several technologies—renewable, microgeneration, new nuclear—are cost competitive now with new coal power plant cost of electricity. The UK should review $CO_2$ policy across all sectors to ensure strong price signals to induce investment in carbon abatement technology across all energy sectors now. The current policy path will be more expensive for the UK, especially since later CCS upgrades will most likely be necessary.

Another major finding is that if CCS is not installed in coal plants, it is highly unlikely that the UK can meet future carbon targets. The timing is right for immediate policymaker and investor reaction because two-thirds of existing UK coal plants have plans for immediate-term FGD-retrofit. Instead, stringent UK policy would induce these plant owners to invest in supercritical, clean technology now in the most long-term cost-effective manner to achieve future energy policy goals. It would also avoid investments in stand-alone FGD-retrofits, a cost-inefficient way to invest in cleaning up plant emissions, and should encourage these plant owners to invest in other, more sustainable technologies and policies, with the focus on distributed generation renewables and energy efficiency. This means that UK policymakers should support stringent coal policy now to send strong price signals to invest immediately in new clean coal infrastructure and/or other renewable technologies rather than face a costly further delay of energy system investment.

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## Appendix A—Binomial Lattice Calculation Process

### Table 13 Outcome Lattice Calculation Process

| 0 Years ($P_0$) | 1 Years (P1) | 2 Years (P2) | 3 Years (P3) | 4 Years (P4) | 25 Years (P25) | Step |
|---|---|---|---|---|---|---|
| Starting Price = $P_0$ | $P1_1 = P_0$*up | $P2_1 = P1_1$*up | $P3_1 = P2_1$*up | $P4_1 = P3_1$*up | $P25_1 = P4_1$*up | 25 |
| | $P1_2 = P_0$*down | $P2_2 = P1_1$*down + $P1_2$*up | $P3_2 = P2_1$*down + $P2_2$*up | $P4_2 = P3_1$*down + $P3_2$*up | $P25_2 = P24_1$*down + $P24_2$*up | 24 |
| | | $P2_3 = P1_2$*down | $P3_3 = P2_2$*down + $P2_3$*up | $P4_3 = P3_2$*down + $P3_3$*up | $P25_3 = P24_2$*down + $P24_3$*up | 23 |
| | | | $P3_4 = P2_3$*down | $P4_4 = P3_3$*down + $P3_4$*up | $P25_4 = P24_3$*down + $P4_4$*up | 22 |
| | | | | $P4_5 = P3_4$*down | $P25_5 = P4_4$*down + $P4_5$*up | 21 |
| | | | | | $P25_6 = P24_5$*down<br>…<br>$P25_{26} = P24_{25}$*down | 20<br>…<br>0 |

### Table 14 Lattice Node Probability Calculation Process

| 3 | 1 Year (p1) | 2 Years (P2) | 3 Years (p3) | 4 Years (p4) | 25 Years (p25) | Step |
|---|---|---|---|---|---|---|
| Starting prob = $p_0$ | $p1_1 = p_0$*p | $P2_1 = p1_1$*p | $p3_1 = p2_1$*p | $p4_1 = p3_1$*p | $p5_1 = p4_1$*p | 25 |
| | $p1_2 = p_0$*(1-p) | $P2_2 = p1_1$*(1-p) + $p1_2$*p | $p3_2 = p2_1$*(1-p) + $p2_2$*p | $p4_2 = p3_1$*(1-p) + $p3_2$*p | $p5_2 = p4_1$*(1-p) + $p4_2$*p | 24 |
| | | $p2_3 = p1_2$*(1-p) | $p3_3 = p2_2$*(1-p) + $p2_3$*p | $p4_3 = p3_2$*(1-p) + $p3_3$*p | $p5_3 = p4_2$*(1-p) + $p4_3$*p | 23 |
| | | | $p3_4 = p2_3$*(1-p) | $p4_4 = p3_3$*(1-p) + $p3_4$*p | $p5_4 = p4_3$*(1-p) + $p4_4$*p | 22 |
| | | | | $p4_5 = p3_4$*(1-p) | $p5_5 = p4_4$*(1-p) + $p4_5$*p | 21 |
| | | | | | $p5_6 = p3_5$*(1-p) + $p4_6$*p<br>…<br>$p5_{26} = p4_{25}$*(1-p) | 20<br>…<br>0 |

## Table 15 Carbon Price Binomial Lattice

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 21 | 22 | 23 (Year 2030) | 24 | 25 | Step |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ 4.55 | £ 6.04 | £ 8.04 | £ 10.69 | £ 14.21 | £ 18.90 | £ 78.59 | £ 326.76 | £ 1,358.63 | £ 1,806.65 | £ 2,402.41 | £ 3,194.64 | £ 4,248.11 | £ 5,648.98 | 25 |
| | £ 3.42 | £ 4.55 | £ 6.04 | £ 8.04 | £ 10.69 | £ 44.44 | £ 184.79 | £ 768.34 | £ 1,021.71 | £ 1,358.63 | £ 1,806.65 | £ 2,402.41 | £ 3,194.64 | 24 |
| | | £ 2.57 | £ 3.42 | £ 4.55 | £ 6.04 | £ 25.13 | £ 104.50 | £ 434.51 | £ 577.80 | £ 768.34 | £ 1,021.71 | £ 1,358.63 | £ 1,806.65 | 23 |
| | | | £ 1.93 | £ 2.57 | £ 3.42 | £ 14.21 | £ 59.10 | £ 245.73 | £ 326.76 | £ 434.51 | £ 577.80 | £ 768.34 | £ 1,021.71 | 22 |
| | | | | £ 1.45 | £ 1.93 | £ 8.04 | £ 33.42 | £ 138.97 | £ 184.79 | £ 245.73 | £ 326.76 | £ 434.51 | £ 577.80 | 21 |
| | | | | | £ 1.09 | £ 4.55 | £ 18.90 | £ 78.59 | £ 104.50 | £ 138.97 | £ 184.79 | £ 245.73 | £ 326.76 | 20 |
| | | | | | | £ 2.57 | £ 10.69 | £ 44.44 | £ 59.10 | £ 78.59 | £ 104.50 | £ 138.97 | £ 184.79 | 19 |
| | | | | | | £ 1.45 | £ 6.04 | £ 25.13 | £ 33.42 | £ 44.44 | £ 59.10 | £ 78.59 | £ 104.50 | 18 |
| | | | | | | £ 0.82 | £ 3.42 | £ 14.21 | £ 18.90 | £ 25.13 | £ 33.42 | £ 44.44 | £ 59.10 | 17 |
| | | | | | | £ 0.46 | £ 1.93 | £ 8.04 | £ 10.69 | £ 14.21 | £ 18.90 | £ 25.13 | £ 33.42 | 16 |
| | | | | | | £ 0.26 | £ 1.09 | £ 4.55 | £ 6.04 | £ 8.04 | £ 10.69 | £ 14.21 | £ 18.90 | 15 |
| | | | | | | | £ 0.62 | £ 2.57 | £ 3.42 | £ 4.55 | £ 6.04 | £ 8.04 | £ 10.69 | 14 |
| | | | | | | | £ 0.35 | £ 1.45 | £ 1.93 | £ 2.57 | £ 3.42 | £ 4.55 | £ 6.04 | 13 |
| | | | | | | | £ 0.20 | £ 0.82 | £ 1.09 | £ 1.45 | £ 1.93 | £ 2.57 | £ 3.42 | 12 |
| | | | | | | | £ 0.11 | £ 0.46 | £ 0.62 | £ 0.82 | £ 1.09 | £ 1.45 | £ 1.93 | 11 |
| | | | | | | | £ 0.06 | £ 0.26 | £ 0.35 | £ 0.46 | £ 0.62 | £ 0.82 | £ 1.09 | 10 |
| | | | | | | | | £ 0.15 | £ 0.20 | £ 0.26 | £ 0.35 | £ 0.46 | £ 0.62 | 9 |
| | | | | | | | | £ 0.08 | £ 0.11 | £ 0.15 | £ 0.20 | £ 0.26 | £ 0.35 | 8 |
| | | | | | | | | £ 0.05 | £ 0.06 | £ 0.08 | £ 0.11 | £ 0.15 | £ 0.20 | 7 |
| | | | | | | | | £ 0.03 | £ 0.04 | £ 0.05 | £ 0.06 | £ 0.08 | £ 0.11 | 6 |
| | | | | | | | | £ 0.02 | £ 0.02 | £ 0.03 | £ 0.04 | £ 0.05 | £ 0.06 | 5 |
| | | | | | | | | | £ 0.01 | £ 0.02 | £ 0.02 | £ 0.03 | £ 0.04 | 4 |
| | | | | | | | | | | £ 0.01 | £ 0.01 | £ 0.02 | £ 0.02 | 3 |
| | | | | | | | | | | | £ 0.01 | £ 0.01 | £ 0.01 | 2 |
| | | | | | | | | | | | | £ 0.00 | £ 0.01 | 1 |
| | | | | | | | | | | | | | £ 0.00 | 0 |

## Table 17 Carbon Probability Binomial Lattice

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 21 | 22 | 23 | 24 | 25 | Step |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | 0.72 | 0.51 | 0.37 | 0.26 | 0.19 | 0.04 | 0.01 | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 25.00 |
| | 0.28 | 0.41 | 0.44 | 0.42 | 0.37 | 0.14 | 0.04 | 0.01 | 0.01 | 0.01 | 0.004 | 0.00 | 0.00 | 24.00 |
| | | 0.08 | 0.17 | 0.25 | 0.30 | 0.25 | 0.11 | 0.04 | 0.03 | 0.02 | 0.019 | 0.01 | 0.01 | 23.00 |
| | | | 0.02 | 0.06 | 0.12 | 0.26 | 0.19 | 0.09 | 0.08 | 0.06 | 0.052 | 0.04 | 0.03 | 22.00 |
| | | | | 0.01 | 0.02 | 0.18 | 0.23 | 0.15 | 0.13 | 0.12 | 0.102 | 0.09 | 0.08 | 21.00 |
| | | | | | 0.00 | 0.09 | 0.20 | 0.19 | 0.18 | 0.17 | 0.153 | 0.14 | 0.12 | 20.00 |
| | | | | | | 0.03 | 0.13 | 0.19 | 0.19 | 0.19 | 0.181 | 0.17 | 0.16 | 19.00 |
| | | | | | | 0.01 | 0.07 | 0.15 | 0.16 | 0.17 | 0.174 | 0.18 | 0.18 | 18.00 |
| | | | | | | 0.00 | 0.03 | 0.10 | 0.11 | 0.12 | 0.137 | 0.15 | 0.16 | 17.00 |
| | | | | | | 0.00 | 0.01 | 0.05 | 0.06 | 0.08 | 0.090 | 0.10 | 0.12 | 16.00 |
| | | | | | | 0.00 | 0.00 | 0.02 | 0.03 | 0.04 | 0.050 | 0.06 | 0.07 | 15.00 |
| | | | | | | | 0.00 | 0.01 | 0.01 | 0.02 | 0.023 | 0.03 | 0.04 | 14.00 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.01 | 0.009 | 0.01 | 0.02 | 13.00 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.003 | 0.00 | 0.01 | 12.00 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.001 | 0.00 | 0.00 | 11.00 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 10.00 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 9.00 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 8.00 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 7.00 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 6.00 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 5.00 |
| | | | | | | | | | 0.00 | 0.00 | 0.000 | 0.00 | 0.00 | 4.00 |
| | | | | | | | | | | 0.00 | 0.000 | 0.00 | 0.00 | 3.00 |
| | | | | | | | | | | | 0.000 | 0.00 | 0.00 | 2.00 |
| | | | | | | | | | | | | 0.00 | 0.00 | 1.00 |
| | | | | | | | | | | | | | 0.00 | 0.00 |
| Sum | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |

## Table 16 Carbon Price Summary

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 21 | 22 | 23 (Year 2030) | 24 | 25 | Step |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ 4.55 | £ 5.30 | £ 6.18 | £ 7.21 | £ 8.41 | £ 9.81 | £ 21.19 | £ 45.74 | £ 115.16 | £ 134.32 | £ 156.67 | £ 182.74 | £ 213.15 | Mean |
| £ 1.30 | £ 1.51 | £ 1.76 | £ 2.06 | £ 2.40 | £ 2.80 | £ 6.04 | £ 13.03 | £ 32.82 | £ 38.28 | £ 44.65 | £ 52.08 | £ 60.75 | Std Dev |
| £ 8.43 | £ 9.84 | £11.47 | £ 13.38 | £15.61 | £ 18.20 | £ 39.30 | £ 84.84 | £ 213.63 | £ 249.17 | £ 290.63 | £ 338.99 | £ 395.39 | Max |
| £ 0.66 | £ 0.77 | £ 0.90 | £ 1.05 | £ 1.22 | £ 1.42 | £ 3.07 | £ 6.63 | £ 16.70 | £ 19.48 | £ 22.72 | £ 26.50 | £ 30.91 | Min |
| | | | | | | | | | | $ 616.08 | per ton | | Max |
| | | | | | | | | | | $ 48.16 | per ton | | Min |
| Exchange Rate | | 1.92308 | | | Tonne Rate | 1.102312 | | | | $ 332.12 | per ton | | Mean |

## Table 18  Low Sulfur Coal Price Binomial Lattice

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 21 | 22 | **23** | 24 | 25 | Step |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ 27.08 | £ 30.72 | £ 34.84 | £ 39.51 | £ 44.81 | £ 50.82 | £ 95.36 | £ 178.93 | £ 335.73 | £ 380.76 | £ 431.84 | **£ 489.76** | £ 555.46 | £ 629.96 | 25 |
| | £ 23.88 | £ 27.08 | £ 30.72 | £ 34.84 | £ 39.51 | £ 74.13 | £ 139.11 | £ 261.01 | £ 296.03 | £ 335.73 | **£ 380.76** | £ 431.84 | £ 489.76 | 24 |
| | | £ 21.06 | £ 23.88 | £ 27.08 | £ 30.72 | £ 57.64 | £ 108.15 | £ 202.93 | £ 230.14 | £ 261.01 | **£ 296.03** | £ 335.73 | £ 380.76 | 23 |
| | | | £ 18.57 | £ 21.06 | £ 23.88 | £ 44.81 | £ 84.08 | £ 157.76 | £ 178.93 | £ 202.93 | **£ 230.14** | £ 261.01 | £ 296.03 | 22 |
| | | | | £ 16.37 | £ 18.57 | £ 34.84 | £ 65.37 | £ 122.65 | £ 139.11 | £ 157.76 | **£ 178.93** | £ 202.93 | £ 230.14 | 21 |
| | | | | | £ 14.43 | £ 27.08 | £ 50.82 | £ 95.36 | £ 108.15 | £ 122.65 | **£ 139.11** | £ 157.76 | £ 178.93 | 20 |
| | | | | | | £ 21.06 | £ 39.51 | £ 74.13 | £ 84.08 | £ 95.36 | **£ 108.15** | £ 122.65 | £ 139.11 | 19 |
| | | | | | | £ 16.37 | £ 30.72 | £ 57.64 | £ 65.37 | £ 74.13 | **£ 84.08** | £ 95.36 | £ 108.15 | 18 |
| | | | | | | £ 12.73 | £ 23.88 | £ 44.81 | £ 50.82 | £ 57.64 | **£ 65.37** | £ 74.13 | £ 84.08 | 17 |
| | | | | | | £ 9.89 | £ 18.57 | £ 34.84 | £ 39.51 | £ 44.81 | **£ 50.82** | £ 57.64 | £ 65.37 | 16 |
| | | | | | | £ 7.69 | £ 14.43 | £ 27.08 | £ 30.72 | £ 34.84 | **£ 39.51** | £ 44.81 | £ 50.82 | 15 |
| | | | | | | | £ 11.22 | £ 21.06 | £ 23.88 | £ 27.08 | **£ 30.72** | £ 34.84 | £ 39.51 | 14 |
| | | | | | | | £ 8.72 | £ 16.37 | £ 18.57 | £ 21.06 | **£ 23.88** | £ 27.08 | £ 30.72 | 13 |
| | | | | | | | £ 6.78 | £ 12.73 | £ 14.43 | £ 16.37 | **£ 18.57** | £ 21.06 | £ 23.88 | 12 |
| | | | | | | | £ 5.27 | £ 9.89 | £ 11.22 | £ 12.73 | **£ 14.43** | £ 16.37 | £ 18.57 | 11 |
| | | | | | | | £ 4.10 | £ 7.69 | £ 8.72 | £ 9.89 | **£ 11.22** | £ 12.73 | £ 14.43 | 10 |
| | | | | | | | | £ 5.98 | £ 6.78 | £ 7.69 | **£ 8.72** | £ 9.89 | £ 11.22 | 9 |
| | | | | | | | | £ 4.65 | £ 5.27 | £ 5.98 | **£ 6.78** | £ 7.69 | £ 8.72 | 8 |
| | | | | | | | | £ 3.61 | £ 4.10 | £ 4.65 | **£ 5.27** | £ 5.98 | £ 6.78 | 7 |
| | | | | | | | | £ 2.81 | £ 3.19 | £ 3.61 | **£ 4.10** | £ 4.65 | £ 5.27 | 6 |
| | | | | | | | | £ 2.18 | £ 2.48 | £ 2.81 | **£ 3.19** | £ 3.61 | £ 4.10 | 5 |
| | | | | | | | | | £ 1.93 | £ 2.18 | **£ 2.48** | £ 2.81 | £ 3.19 | 4 |
| | | | | | | | | | | £ 1.70 | **£ 1.93** | £ 2.18 | £ 2.48 | 3 |
| | | | | | | | | | | | **£ 1.50** | £ 1.70 | £ 1.93 | 2 |
| | | | | | | | | | | | | £ 1.32 | £ 1.50 | 1 |
| | | | | | | | | | | | | | £ 1.16 | 0 |

## Table 20 Low Sulfur Coal Probability Binomial Lattice

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 21 | 22 | **23** | 24 | 25 | Step |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | 0.68 | 0.47 | 0.32 | 0.22 | 0.15 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 25 |
| | 0.32 | 0.43 | 0.44 | 0.40 | 0.34 | 0.10 | 0.02 | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 24 |
| | | 0.10 | 0.21 | 0.28 | 0.32 | 0.21 | 0.07 | 0.02 | 0.02 | 0.01 | **0.01** | 0.01 | 0.00 | 23 |
| | | | 0.03 | 0.09 | 0.15 | 0.26 | 0.15 | 0.06 | 0.04 | 0.03 | **0.03** | 0.02 | 0.02 | 22 |
| | | | | 0.01 | 0.03 | 0.22 | 0.21 | 0.11 | 0.09 | 0.08 | **0.06** | 0.05 | 0.04 | 21 |
| | | | | | 0.00 | 0.12 | 0.21 | 0.16 | 0.15 | 0.13 | **0.11** | 0.10 | 0.08 | 20 |
| | | | | | | 0.05 | 0.16 | 0.19 | 0.18 | 0.17 | **0.16** | 0.14 | 0.13 | 19 |
| | | | | | | 0.01 | 0.10 | 0.18 | 0.18 | 0.18 | **0.18** | 0.17 | 0.16 | 18 |
| | | | | | | 0.00 | 0.05 | 0.13 | 0.15 | 0.16 | **0.16** | 0.17 | 0.17 | 17 |
| | | | | | | 0.00 | 0.02 | 0.08 | 0.10 | 0.11 | **0.13** | 0.14 | 0.15 | 16 |
| | | | | | | 0.00 | 0.00 | 0.04 | 0.05 | 0.07 | **0.08** | 0.10 | 0.11 | 15 |
| | | | | | | | 0.00 | 0.02 | 0.03 | 0.03 | **0.05** | 0.06 | 0.07 | 14 |
| | | | | | | | 0.00 | 0.01 | 0.01 | 0.01 | **0.02** | 0.03 | 0.04 | 13 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.01 | **0.01** | 0.01 | 0.02 | 12 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.01 | 11 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 10 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 9 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 8 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 7 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 6 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 5 |
| | | | | | | | | | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | 4 |
| | | | | | | | | | | 0.00 | **0.00** | 0.00 | 0.00 | 3 |
| | | | | | | | | | | | **0.00** | 0.00 | 0.00 | 2 |
| | | | | | | | | | | | | 0.00 | 0.00 | 1 |
| | | | | | | | | | | | | | 0.00 | 0 |

## Table 19 Low Sulfur Coal Price Summary

| 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2017 | 2022 | 2027 | 2028 | 2029 | **2030** | 2031 | 2032 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ 37.31 | £ 39.33 | £ 41.46 | £ 43.70 | £ 46.06 | £ 48.55 | £ 63.18 | £ 82.21 | £ 106.98 | £ 112.76 | £ 118.86 | £ 125.29 | £ 132.07 | £ 139.21 | Max |
| £ 16.86 | £ 17.77 | £ 18.73 | £ 19.74 | £ 20.81 | £ 21.94 | £ 28.54 | £ 37.14 | £ 48.33 | £ 50.95 | £ 53.70 | £ 56.60 | £ 59.67 | £ 62.89 | Min |
| £ 27.08 | £ 28.55 | £ 30.09 | £ 31.72 | £ 33.44 | £ 35.24 | £ 45.86 | £ 59.68 | £ 77.66 | £ 81.85 | £ 86.28 | £ 90.95 | £ 95.87 | £ 101.05 | Median |
| | | | | | | | | | | | $ 265.59 | per ton | Max | |
| | | | | | | | | | | | $ 119.99 | per ton | Min | |
| | | | | | | | | | | | $ 192.79 | per ton | Median | |

## Table 21 Medium Sulfur Coal Price Binomial Lattice

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ 20.06 | £ 22.62 | £ 25.50 | £ 28.76 | £ 32.42 | £ 36.56 | £ 66.61 | £ 121.37 | £ 221.15 | £ 249.34 | £ 281.13 | £ 316.98 | £ 357.39 | £ 402.96 |
| | £ 17.79 | £ 20.06 | £ 22.62 | £ 25.50 | £ 28.76 | £ 52.40 | £ 95.47 | £ 173.96 | £ 196.14 | £ 221.15 | £ 249.34 | £ 281.13 | £ 316.98 |
| | | £ 15.78 | £ 17.79 | £ 20.06 | £ 22.62 | £ 41.22 | £ 75.10 | £ 136.84 | £ 154.29 | £ 173.96 | £ 196.14 | £ 221.15 | £ 249.34 |
| | | | £ 14.00 | £ 15.78 | £ 17.79 | £ 32.42 | £ 59.08 | £ 107.64 | £ 121.37 | £ 136.84 | £ 154.29 | £ 173.96 | £ 196.14 |
| | | | | £ 12.41 | £ 14.00 | £ 25.50 | £ 46.47 | £ 84.68 | £ 95.47 | £ 107.64 | £ 121.37 | £ 136.84 | £ 154.29 |
| | | | | | £ 11.01 | £ 20.06 | £ 36.56 | £ 66.61 | £ 75.10 | £ 84.68 | £ 95.47 | £ 107.64 | £ 121.37 |
| | | | | | | £ 15.78 | £ 28.76 | £ 52.40 | £ 59.08 | £ 66.61 | £ 75.10 | £ 84.68 | £ 95.47 |
| | | | | | | £ 12.41 | £ 22.62 | £ 41.22 | £ 46.47 | £ 52.40 | £ 59.08 | £ 66.61 | £ 75.10 |
| | | | | | | £ 9.77 | £ 17.79 | £ 32.42 | £ 36.56 | £ 41.22 | £ 46.47 | £ 52.40 | £ 59.08 |
| | | | | | | £ 7.68 | £ 14.00 | £ 25.50 | £ 28.76 | £ 32.42 | £ 36.56 | £ 41.22 | £ 46.47 |
| | | | | | | £ 6.04 | £ 11.01 | £ 20.06 | £ 22.62 | £ 25.50 | £ 28.76 | £ 32.42 | £ 36.56 |
| | | | | | | | £ 8.66 | £ 15.78 | £ 17.79 | £ 20.06 | £ 22.62 | £ 25.50 | £ 28.76 |
| | | | | | | | £ 6.81 | £ 12.41 | £ 14.00 | £ 15.78 | £ 17.79 | £ 20.06 | £ 22.62 |
| | | | | | | | £ 5.36 | £ 9.77 | £ 11.01 | £ 12.41 | £ 14.00 | £ 15.78 | £ 17.79 |
| | | | | | | | £ 4.22 | £ 7.68 | £ 8.66 | £ 9.77 | £ 11.01 | £ 12.41 | £ 14.00 |
| | | | | | | | £ 3.32 | £ 6.04 | £ 6.81 | £ 7.68 | £ 8.66 | £ 9.77 | £ 11.01 |
| | | | | | | | | £ 4.75 | £ 5.36 | £ 6.04 | £ 6.81 | £ 7.68 | £ 8.66 |
| | | | | | | | | £ 3.74 | £ 4.22 | £ 4.75 | £ 5.36 | £ 6.04 | £ 6.81 |
| | | | | | | | | £ 2.94 | £ 3.32 | £ 3.74 | £ 4.22 | £ 4.75 | £ 5.36 |
| | | | | | | | | £ 2.31 | £ 2.61 | £ 2.94 | £ 3.32 | £ 3.74 | £ 4.22 |
| | | | | | | | | £ 1.82 | £ 2.05 | £ 2.31 | £ 2.61 | £ 2.94 | £ 3.32 |
| | | | | | | | | | £ 1.61 | £ 1.82 | £ 2.05 | £ 2.31 | £ 2.61 |
| | | | | | | | | | | £ 1.43 | £ 1.61 | £ 1.82 | £ 2.05 |
| | | | | | | | | | | | £ 1.27 | £ 1.43 | £ 1.61 |
| | | | | | | | | | | | | £ 1.13 | £ 1.27 |
| | | | | | | | | | | | | | £ 1.00 |

## Table 22 Medium Sulfur Coal Probability Binomial Lattice

| 0 | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 21 | 22 | 23 | 24 | 25 | Step |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | 0.61 | 0.37 | 0.23 | 0.14 | 0.09 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 25 |
| | 0.39 | 0.48 | 0.44 | 0.36 | 0.27 | 0.05 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 24 |
| | | 0.15 | 0.28 | 0.34 | 0.35 | 0.13 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 23 |
| | | | 0.06 | 0.14 | 0.22 | 0.22 | 0.07 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 22 |
| | | | | 0.02 | 0.07 | 0.25 | 0.14 | 0.04 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 21 |
| | | | | | 0.01 | 0.19 | 0.19 | 0.09 | 0.07 | 0.05 | 0.04 | 0.03 | 0.03 | 20 |
| | | | | | | 0.10 | 0.21 | 0.14 | 0.12 | 0.10 | 0.08 | 0.07 | 0.05 | 19 |
| | | | | | | 0.04 | 0.17 | 0.17 | 0.16 | 0.14 | 0.12 | 0.11 | 0.09 | 18 |
| | | | | | | 0.01 | 0.11 | 0.18 | 0.18 | 0.17 | 0.16 | 0.15 | 0.13 | 17 |
| | | | | | | 0.00 | 0.05 | 0.15 | 0.16 | 0.17 | 0.17 | 0.16 | 0.16 | 16 |
| | | | | | | 0.00 | 0.02 | 0.11 | 0.12 | 0.14 | 0.15 | 0.16 | 0.16 | 15 |
| | | | | | | | 0.01 | 0.06 | 0.08 | 0.10 | 0.11 | 0.13 | 0.14 | 14 |
| | | | | | | | 0.00 | 0.03 | 0.04 | 0.06 | 0.07 | 0.09 | 0.10 | 13 |
| | | | | | | | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.07 | 12 |
| | | | | | | | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 11 |
| | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 10 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 9 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 8 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 7 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 6 |
| | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 |
| | | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4 |
| | | | | | | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 3 |
| | | | | | | | | | | | 0.00 | 0.00 | 0.00 | 2 |
| | | | | | | | | | | | | 0.00 | 0.00 | 1 |
| | | | | | | | | | | | | | 0.00 | 0.00 |

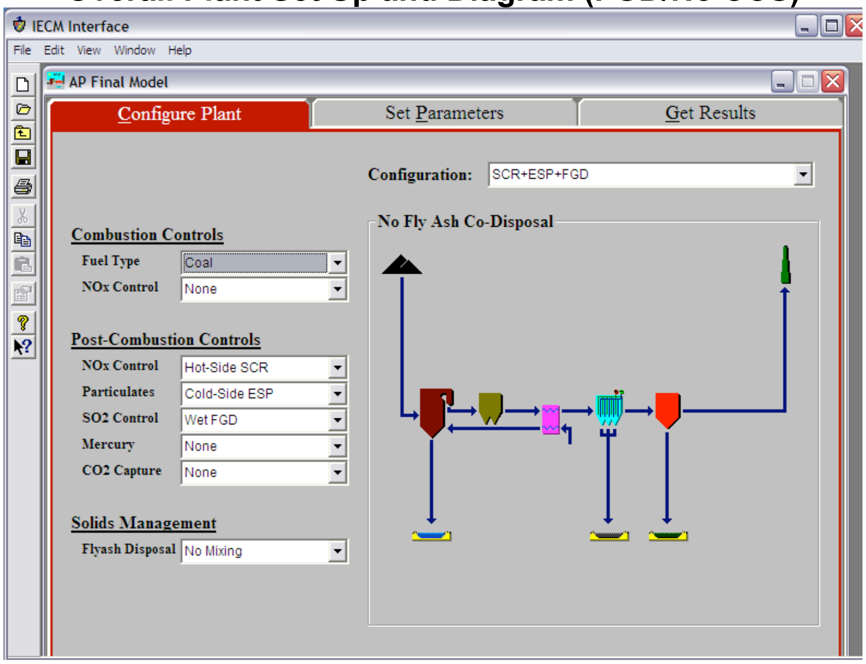
## Table 23 Medium Sulfur Coal Price Summary

| 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2017 | 2022 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ 27.28 | £ 28.21 | £ 29.17 | £ 30.16 | £ 31.19 | £ 32.24 | £ 38.11 | £ 45.04 | £ 53.22 | £ 55.03 | £ 56.90 | £ 58.83 | £ 60.83 | £ 62.90 | Max |
| £ 12.84 | £ 13.28 | £ 13.73 | £ 14.19 | £ 14.68 | £ 15.17 | £ 17.93 | £ 21.19 | £ 25.05 | £ 25.90 | £ 26.78 | £ 27.69 | £ 28.63 | £ 29.60 | Min |
| £ 20.06 | £ 20.74 | £ 21.45 | £ 22.18 | £ 22.93 | £ 23.71 | £ 28.02 | £ 33.11 | £ 39.13 | £ 40.46 | £ 41.84 | £ 43.26 | £ 44.73 | £ 46.25 | Median |
| | | | | | | | | | | | $ 124.72 | per ton | Max | |
| | | | | | | | | | | | $ 58.69 | per ton | Min | |
| | | | | | | | | | | | $ 91.70 | per ton | Median | |

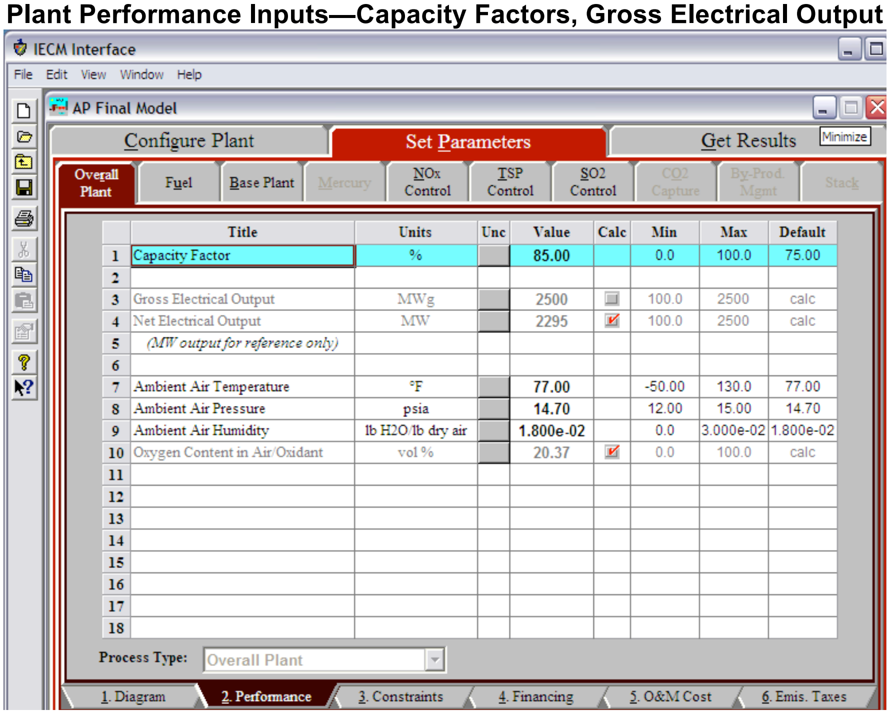
## Appendix B—IECM Model Inputs and Outputs Selected Screenshots

Scenario 1—Low Sulfur Coal, Low Price, Low Carbon Price

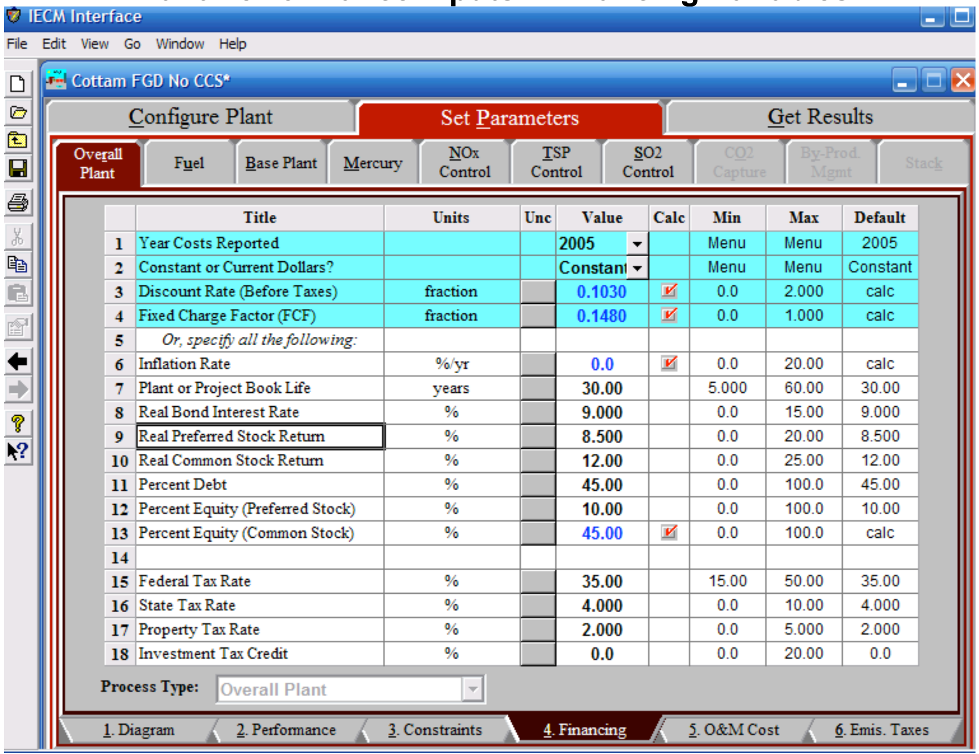
### Overall Plant Set Up and Diagram (FGD/No CCS)




### Plant Performance Inputs—Capacity Factors, Gross Electrical Output

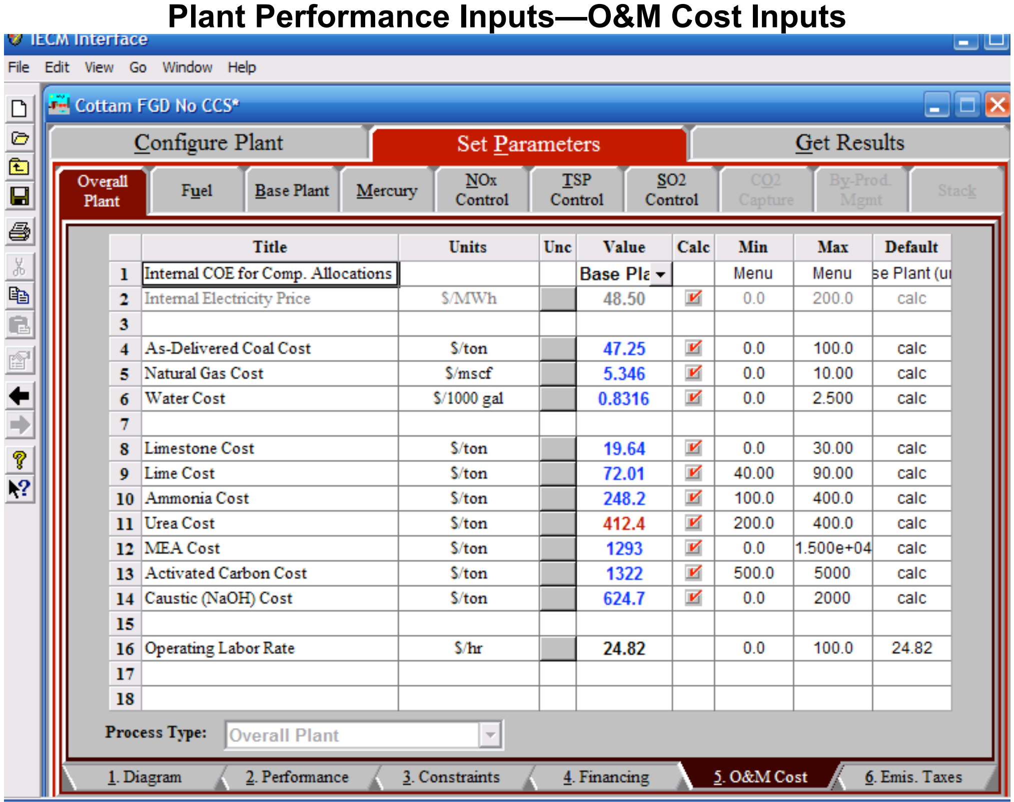


## Plant Performance Inputs—Financing Variables



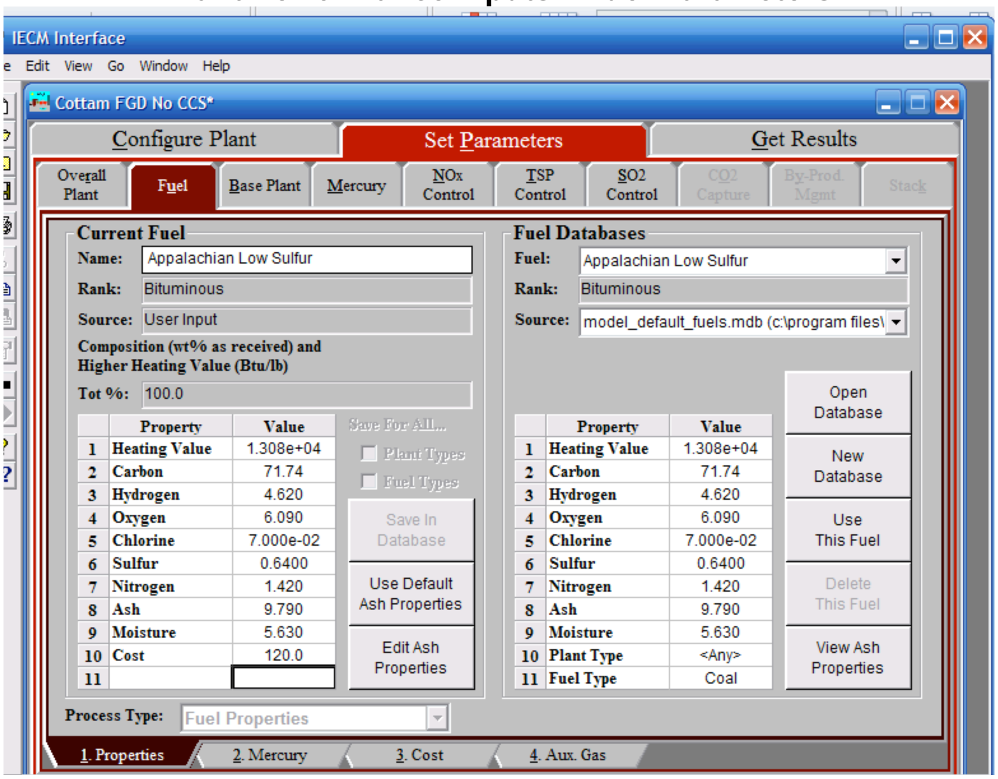

| | Title | Units | Unc | Value | Calc | Min | Max | Default |
|---|---|---|---|---|---|---|---|---|
| 1 | Year Costs Reported | | | 2005 | | Menu | Menu | 2005 |
| 2 | Constant or Current Dollars? | | | Constant | | Menu | Menu | Constant |
| 3 | Discount Rate (Before Taxes) | fraction | | 0.1030 | ✓ | 0.0 | 2.000 | calc |
| 4 | Fixed Charge Factor (FCF) | fraction | | 0.1480 | ✓ | 0.0 | 1.000 | calc |
| 5 | *Or, specify all the following:* | | | | | | | |
| 6 | Inflation Rate | %/yr | | 0.0 | ✓ | 0.0 | 20.00 | calc |
| 7 | Plant or Project Book Life | years | | 30.00 | | 5.000 | 60.00 | 30.00 |
| 8 | Real Bond Interest Rate | % | | 9.000 | | 0.0 | 15.00 | 9.000 |
| 9 | Real Preferred Stock Return | % | | 8.500 | | 0.0 | 20.00 | 8.500 |
| 10 | Real Common Stock Return | % | | 12.00 | | 0.0 | 25.00 | 12.00 |
| 11 | Percent Debt | % | | 45.00 | | 0.0 | 100.0 | 45.00 |
| 12 | Percent Equity (Preferred Stock) | % | | 10.00 | | 0.0 | 100.0 | 10.00 |
| 13 | Percent Equity (Common Stock) | % | | 45.00 | ✓ | 0.0 | 100.0 | calc |
| 14 | | | | | | | | |
| 15 | Federal Tax Rate | % | | 35.00 | | 15.00 | 50.00 | 35.00 |
| 16 | State Tax Rate | % | | 4.000 | | 0.0 | 10.00 | 4.000 |
| 17 | Property Tax Rate | % | | 2.000 | | 0.0 | 5.000 | 2.000 |
| 18 | Investment Tax Credit | % | | 0.0 | | 0.0 | 20.00 | 0.0 |

## Plant Performance Inputs—O&M Cost Inputs

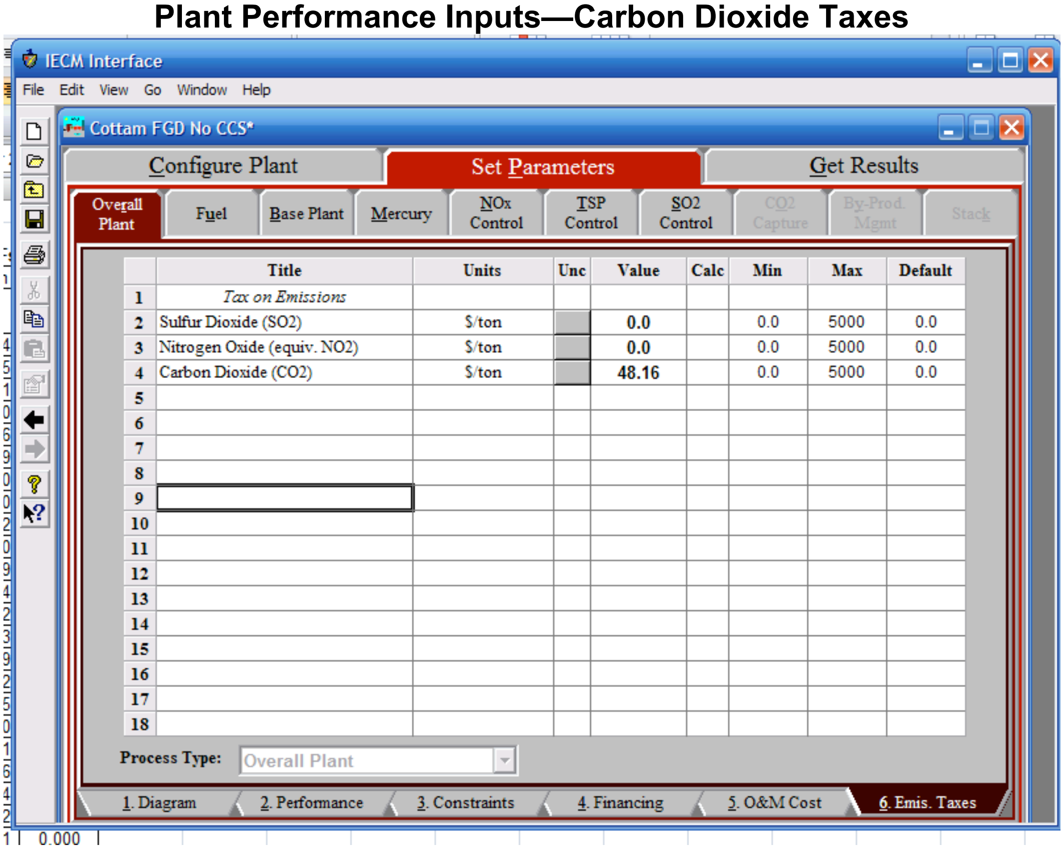



| | Title | Units | Unc | Value | Calc | Min | Max | Default |
|---|---|---|---|---|---|---|---|---|
| 1 | Internal COE for Comp. Allocations | | | Base Pla | | Menu | Menu | se Plant (u |
| 2 | Internal Electricity Price | $/MWh | | 48.50 | ✓ | 0.0 | 200.0 | calc |
| 3 | | | | | | | | |
| 4 | As-Delivered Coal Cost | $/ton | | 47.25 | ✓ | 0.0 | 100.0 | calc |
| 5 | Natural Gas Cost | $/mscf | | 5.346 | ✓ | 0.0 | 10.00 | calc |
| 6 | Water Cost | $/1000 gal | | 0.8316 | ✓ | 0.0 | 2.500 | calc |
| 7 | | | | | | | | |
| 8 | Limestone Cost | $/ton | | 19.64 | ✓ | 0.0 | 30.00 | calc |
| 9 | Lime Cost | $/ton | | 72.01 | ✓ | 40.00 | 90.00 | calc |
| 10 | Ammonia Cost | $/ton | | 248.2 | ✓ | 100.0 | 400.0 | calc |
| 11 | Urea Cost | $/ton | | 412.4 | ✓ | 200.0 | 400.0 | calc |
| 12 | MEA Cost | $/ton | | 1293 | ✓ | 0.0 | 1.500e+04 | calc |
| 13 | Activated Carbon Cost | $/ton | | 1322 | ✓ | 500.0 | 5000 | calc |
| 14 | Caustic (NaOH) Cost | $/ton | | 624.7 | ✓ | 0.0 | 2000 | calc |
| 15 | | | | | | | | |
| 16 | Operating Labor Rate | $/hr | | 24.82 | | 0.0 | 100.0 | 24.82 |
| 17 | | | | | | | | |
| 18 | | | | | | | | |

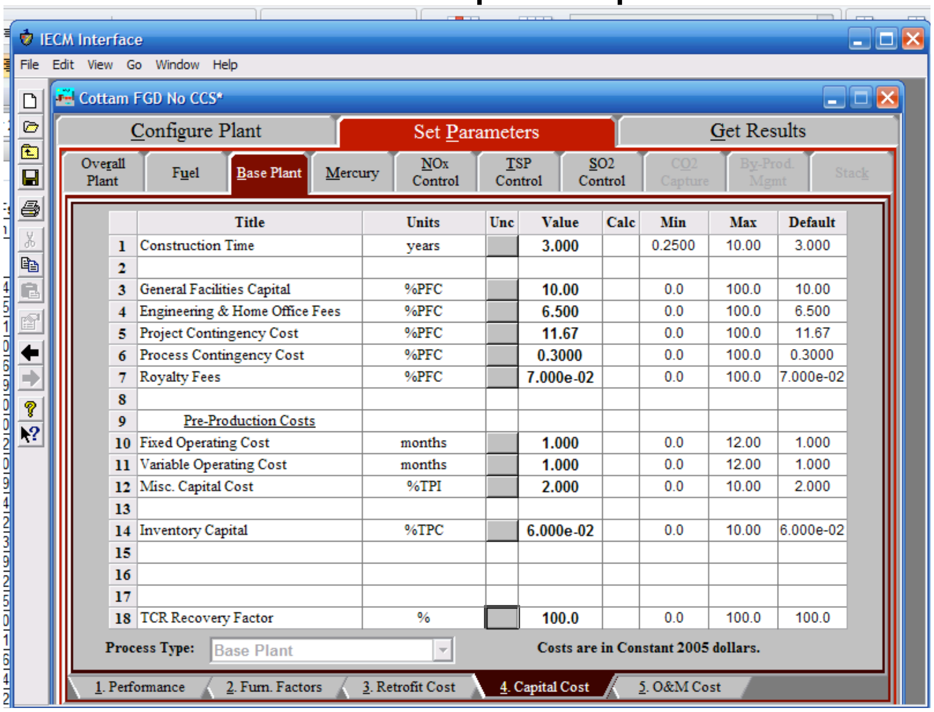
## Plant Performance Inputs—Fuel Parameters




## Plant Performance Inputs—Carbon Dioxide Taxes



## Plant Performance Inputs—Capital Costs



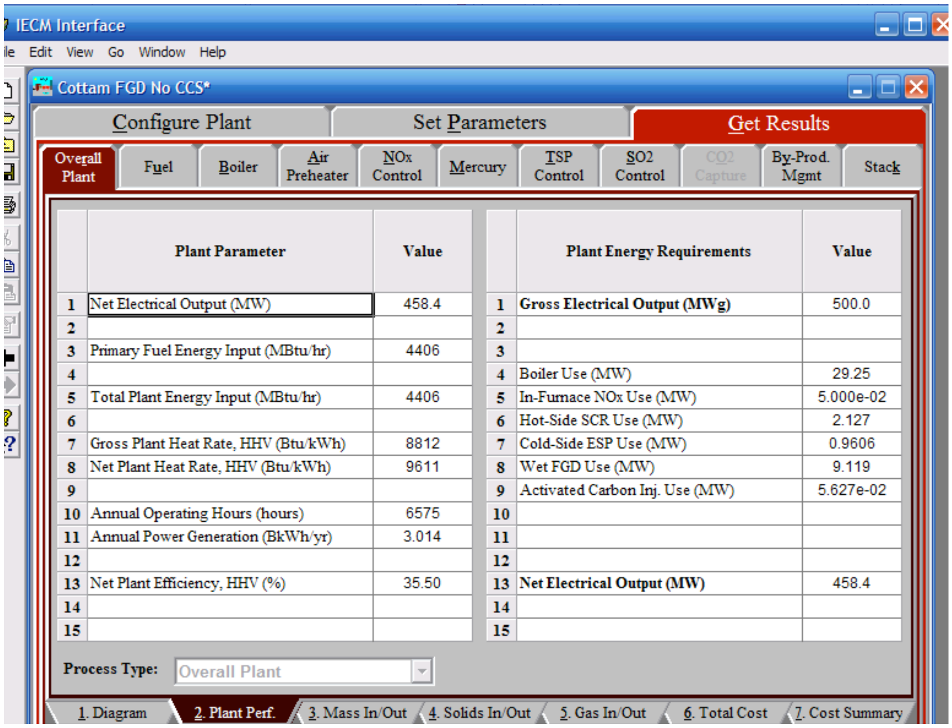

| | Title | Units | Unc | Value | Calc | Min | Max | Default |
|---|---|---|---|---|---|---|---|---|
| 1 | Construction Time | years | | 3.000 | | 0.2500 | 10.00 | 3.000 |
| 2 | | | | | | | | |
| 3 | General Facilities Capital | %PFC | | 10.00 | | 0.0 | 100.0 | 10.00 |
| 4 | Engineering & Home Office Fees | %PFC | | 6.500 | | 0.0 | 100.0 | 6.500 |
| 5 | Project Contingency Cost | %PFC | | 11.67 | | 0.0 | 100.0 | 11.67 |
| 6 | Process Contingency Cost | %PFC | | 0.3000 | | 0.0 | 100.0 | 0.3000 |
| 7 | Royalty Fees | %PFC | | 7.000e-02 | | 0.0 | 100.0 | 7.000e-02 |
| 8 | | | | | | | | |
| 9 | Pre-Production Costs | | | | | | | |
| 10 | Fixed Operating Cost | months | | 1.000 | | 0.0 | 12.00 | 1.000 |
| 11 | Variable Operating Cost | months | | 1.000 | | 0.0 | 12.00 | 1.000 |
| 12 | Misc. Capital Cost | %TPI | | 2.000 | | 0.0 | 10.00 | 2.000 |
| 13 | | | | | | | | |
| 14 | Inventory Capital | %TPC | | 6.000e-02 | | 0.0 | 10.00 | 6.000e-02 |
| 15 | | | | | | | | |
| 16 | | | | | | | | |
| 17 | | | | | | | | |
| 18 | TCR Recovery Factor | % | | 100.0 | | 0.0 | 100.0 | 100.0 |

## Plant Performance Inputs—O&M Costs


| | Title | Units | Unc | Value | Calc | Min | Max | Default |
|---|---|---|---|---|---|---|---|---|
| 1 | As-Delivered Coal Cost | $/ton | | 120.0 | ✓ | 0.0 | 160.0 | calc |
| 2 | Waste Disposal Cost | $/ton | | 9.360 | | 0.0 | 30.00 | 9.360 |
| 3 | Water Use | gallons/kWh | | 1.000 | | 0.0 | 10.00 | 1.000 |
| 4 | Water Cost | $/1000 gal | | 0.8316 | ✓ | 0.0 | 2.500 | calc |
| 5 | Electricity Price (Base Plant) | $/MWh | | 74.85 | ✓ | 0.0 | 200.0 | calc |
| 6 | | | | | | | | |
| 7 | Number of Operating Jobs | number | | 20.00 | | 0.0 | 100.0 | 20.00 |
| 8 | Number of Operating Shifts | shifts/day | | 4.750 | | 0.0 | 10.00 | 4.750 |
| 9 | Operating Labor Rate | $/hr | | 24.82 | | 0.0 | 100.0 | 24.82 |
| 10 | | | | | | | | |
| 11 | Total Maintenance Cost | %TPC | | 1.858 | ✓ | 0.0 | 100.0 | calc |
| 12 | Maint. Cost Allocated to Labor | %TMC | | 35.00 | | 0.0 | 100.0 | 35.00 |
| 13 | Administrative & Support Cost | % total labor | | 7.000 | | 0.0 | 100.0 | 7.000 |
| 14 | | | | | | | | |
| 15 | Real Escalation Rate | %/yr | | 0.0 | | 0.0 | 10.00 | 0.0 |
| 16 | | | | | | | | |
| 17 | | | | | | | | |
| 18 | | | | | | | | |

# Example IECM Power Plant Calculation Results

## Overall Plant Performance

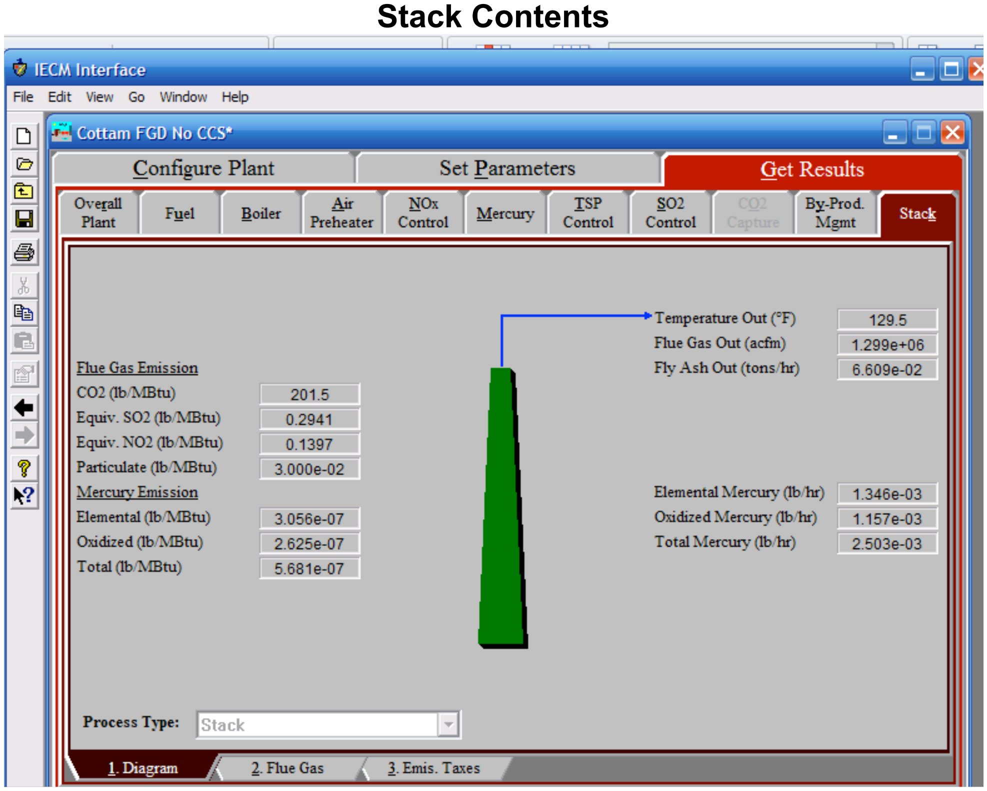


| | Plant Parameter | Value |
|---|---|---|
| 1 | Net Electrical Output (MW) | 458.4 |
| 2 | | |
| 3 | Primary Fuel Energy Input (MBtu/hr) | 4406 |
| 4 | | |
| 5 | Total Plant Energy Input (MBtu/hr) | 4406 |
| 6 | | |
| 7 | Gross Plant Heat Rate, HHV (Btu/kWh) | 8812 |
| 8 | Net Plant Heat Rate, HHV (Btu/kWh) | 9611 |
| 9 | | |
| 10 | Annual Operating Hours (hours) | 6575 |
| 11 | Annual Power Generation (BkWh/yr) | 3.014 |
| 12 | | |
| 13 | Net Plant Efficiency, HHV (%) | 35.50 |
| 14 | | |
| 15 | | |

| | Plant Energy Requirements | Value |
|---|---|---|
| 1 | Gross Electrical Output (MWg) | 500.0 |
| 2 | | |
| 3 | | |
| 4 | Boiler Use (MW) | 29.25 |
| 5 | In-Furnace NOx Use (MW) | 5.000e-02 |
| 6 | Hot-Side SCR Use (MW) | 2.127 |
| 7 | Cold-Side ESP Use (MW) | 0.9606 |
| 8 | Wet FGD Use (MW) | 9.119 |
| 9 | Activated Carbon Inj. Use (MW) | 5.627e-02 |
| 10 | | |
| 11 | | |
| 12 | | |
| 13 | Net Electrical Output (MW) | 458.4 |
| 14 | | |
| 15 | | |



## Stack Contents



## Annual Levelized Plant Fixed and Variable Costs

| | Technology | Fixed O&M (M$/yr) | Variable O&M (M$/yr) | Total O&M (M$/yr) | Annualized Capital (M$/yr) | Total Levelized Annual Cost (M$/yr) |
|---|---|---|---|---|---|---|
| 1 | Combustion NOx Control | 0.1910 | 3.989 | 4.180 | 1.884 | 6.064 |
| 2 | Post-Combustion NOx Control | 0.6704 | 4.357 | 5.027 | 5.776 | 10.80 |
| 3 | Mercury Control | 6.591e-02 | 2.769e-02 | 9.360e-02 | 1.026e-02 | 0.1039 |
| 4 | TSP Control | 0.7967 | 1.663 | 2.459 | 3.792 | 6.251 |
| 5 | SO2 Control | 5.285 | 5.331 | 10.62 | 8.907 | 19.52 |
| 6 | Combined SOx/NOx Control | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 7 | CO2 Capture | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 8 | Subtotal | 7.009 | 15.37 | 22.38 | 20.37 | 42.74 |
| 9 | Base Plant | 15.43 | 129.4 | 144.8 | 80.78 | 225.6 |
| 10 | Emission Taxes | 0.0 | 140.6 | 140.6 | 0.0 | 140.6 |
| 11 | Total | 22.44 | 285.3 | 307.8 | 101.1 | 408.9 |
| 12 | | | | | | |
| 13 | | | | | | |
| 14 | | | | | | |
| 15 | | | | | | |

Process Type: Overall Plant

Costs are in Constant 2005 dollars.

## Annual Levelized Plant Fixed and Variable Costs

| | Technology | Capital Required (M$) | Capital Required ($/kW-net) | Revenue Required (M$/yr) | Revenue Required ($/MWh) |
|---|---|---|---|---|---|
| 1 | Combustion NOx Control | 12.73 | 27.77 | 6.064 | 2.012 |
| 2 | Post-Combustion NOx Control | 39.03 | 85.13 | 10.80 | 3.584 |
| 3 | Mercury Control | 6.933e-02 | 0.1512 | 0.1039 | 3.446e-02 |
| 4 | TSP Control | 25.62 | 55.88 | 6.251 | 2.074 |
| 5 | SO2 Control | 60.19 | 131.3 | 19.52 | 6.477 |
| 6 | Combined SOx/NOx Control | 0.0 | 0.0 | 0.0 | 0.0 |
| 7 | CO2 Capture | 0.0 | 0.0 | 0.0 | 0.0 |
| 8 | Subtotal | 137.6 | 300.2 | 42.74 | 14.18 |
| 9 | Base Plant | 545.8 | 1191 | 225.6 | 74.85 |
| 10 | Emission Taxes | 0.0 | 0.0 | 140.6 | 46.64 |
| 11 | Total | 683.5 | 1491 | 408.9 | 135.7 |
| 12 | | | | | |
| 13 | | | | | |
| 14 | | | | | |
| 15 | | | | | |

Process Type: Overall Plant

Costs are in Constant 2005 dollars.

## Appendix C—Example Spreadsheet Calculations from Model Output

In the two tables below, total levelized capital and O&M costs (shown in bold) are calculated from the IECM iteration outputs (shown in italics).

| Plant Parameter | Value | Plant Energy Requirements | Value |
|---|---|---|---|
| Net Electrical Output (MW) | *459.8* | Gross Electrical Output (MWg) | *500* |
| Primary Fuel Energy Input (MBtu/hr) | *3622* | Boiler Use (MW) | *29.25* |
| Total Plant Energy Input (MBtu/hr) | *3622* | In-Furnace NOx Use (MW) | *5.00E-02* |
| Gross Plant Heat Rate, HHV (Btu/kWh) | *7243* | Hot-Side SCR Use (MW) | *2.158* |
| Net Plant Heat Rate, HHV (Btu/kWh) | *7876* | Cold-Side ESP Use (MW) | *0.9125* |
| Annual Operating Hours (hours) | *6575* | Wet FGD Use (MW) | *7.754* |
| Annual Power Generation (BkWh/yr) | *3.023* | Activated Carbon Inj. Use (MW) | *4.75E-02* |
| Net Plant Efficiency, HHV (%) | *43%* | Net Electrical Output (MW) | *459.8* |

**Scenario 4 Example Calculation**
**500 MW New Supercritical Boiler Plant**
**FGD, No CCS, Med S, Low Coal Price, Medium Carbon Price**

| Technology | Capital Required ($/kW-net) | Capital Required (£/kW) | Revenue Required ($/MWh) | Total Levelized Cost (£/kWh) | Fixed O&M (M$/yr) | Variable O&M (M$/yr) | Total O&M (M$/yr) | Total O&M Cost (£/kWh) | Annua-lized Capital (M$/yr) | Total Levelized Annual Cost (M$/yr) | Total Levelized Cost (£/kW) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Combustion NOx Control | *$ 32.70* | *£ 17.00* | *$ 1.71* | **£ 0.0009** | *$ 0.23* | *$ 2.82* | *$ 3.05* | **£ 0.0005** | *$ 2.11* | *$ 5.16* | **£ 0.0014** |
| Post-Combustion NOx Control | *$ 41.36* | *£ 21.51* | *$ 1.56* | **£ 0.0008** | *$ 0.50* | *$ 1.54* | *$ 2.05* | **£ 0.0004** | *$ 2.67* | *$ 4.72* | **£ 0.0012** |
| Mercury Control | *$ 0.15* | *£ 0.08* | *$ 0.03* | **£ 0.0000** | *$ 0.07* | *$ 0.02* | *$ 0.08* | **£ 0.0000** | *$ 0.01* | *$ 0.09* | **£ 0.0000** |
| TSP Control | *$ 39.87* | *£ 20.73* | *$ 1.42* | **£ 0.0007** | *$ 0.71* | *$ 1.01* | *$ 1.72* | **£ 0.0003** | *$ 2.57* | *$ 4.29* | **£ 0.0010** |
| SO2 Control | *$ 135.20* | *£ 70.30* | *$ 6.18* | **£ 0.0032** | *$ 5.35* | *$ 4.59* | *$ 9.95* | **£ 0.0017** | *$ 8.72* | *$ 18.67* | **£ 0.0049** |
| CO2 Capture | *$ -* | *£ -* | *$ -* | **£ -** | *$ -* | *$ -* | *$ -* | **£ -** | *$ -* | *$ -* | **£ -** |
| Subtotal | *$ 249.30* | *£ 129.64* | *$ 10.89* | **£ 0.0057** | *$ 6.86* | *$ 9.98* | *$ 16.84* | **£ 0.0029** | *$ 16.09* | *$ 32.93* | **£ 0.0086** |
| Base Plant | *$ 1,248.00* | *£ 648.96* | *$ 48.98* | **£ 0.0255** | *$15.90* | *$ 51.67* | *$ 67.57* | **£ 0.0116** | *$ 80.50* | *$ 148.10* | **£ 0.0371** |
| Emission Taxes | *$ -* | *£ -* | *$ 269.10* | **£ 0.1399** | *$ -* | *$ 813.50* | *$ 813.50* | **£ 0.1399** | *$ -* | *$ 813.50* | **£ 0.2799** |
| **Total** | *$ 1,497.00* | *£ 778.44* | *$ 329.00* | **£ 0.1711** | *$22.76* | *$ 875.20* | *$ 897.90* | **£ 0.1545** | *$ 96.59* | *$ 994.50* | **£ 0.3255** |

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