Analytic Approaches to Quantify and Value Fuel Mix Diversity[1]

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Abstract

Large investment in gas fired power generation over the past two decades have raised concerns in some European liberalised markets that the diversity of the fuel mix would reduce, with potential negative security of supply and macroeconomic impacts. This paper argues that while diversity can be seen as a desirable feature of an electricity system, it is not clear *what* should be diversified, and *how much* diversity is optimal. The different strands of the literature focussing on the *quantification* (diversity indexes) and *valuation* of diversity (Mean Variance Portfolio theory and Real Options theory) are reviewed. This paper serves as an introduction to a book providing a selection of the recent research applying Mean-Variance Portfolio theory to optimize fuel mix diversity and security in liberalised power markets.[3]

Keywords: Fuel mix, diversity, security of supply

1 INTRODUCTION

This paper aims to explore the concept of diversity as applied to an electricity system. It argues that greater diversity generally enhances the robustness of an electricity system to fossil fuel supply shocks, and hence yields macroeconomics and security of supply benefits. This paper points out, however, that a diverse electricity system is not a necessary condition to guarantee security of supply. Besides, this paper argues that the concept of diversity as applied to an electricity system remains ill-defined. It is not clear *what* should be diversified, nor is it straightforward to quantify the *costs* and *benefits* of increased diversity.

The paper then reviews the different analytical approaches to *quantify* and *value* the diversity of an electricity system. It argues that while there have been many attempts to design diversity indicators

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which serve as useful proxies to quantify diversity, such indicators suffer from not taking into account the costs of increased diversity. The paper argues that more research is needed to identify the economic costs associated with greater diversity, as well as to weight the costs and benefits of increased diversity. The paper discusses how new analytical tools borrowed from the financial diversification literature can be used to trade-off the costs and benefits of diversity. These include *static* valuation methods such as Mean-Variance Portfolio Theory, and *dynamic* valuation methods such as Real Options which take into account the option value of diversity as a hedge against potential fossil fuel supply or price shocks.

2 DEFINING THE DIVERSITY OF THE ELECTRICITY SYSTEM

The concept of diversity as applied to electric generation is intuitively appealing at times when the resurgence of political tensions raises questions about the reliability of fossil fuel imports. However, the diversity of an electricity system remains ill-defined, both qualitatively and quantitatively (Roques, 2003). The basic principle of diversity is straightforward – not putting all one's eggs in one basket. But this can apply to a wide range of characteristic features of the electricity system, including the mix of fuels used to generate electricity, plant technology and manufacturers, or plant operators. This paper concentrates on fuel mix diversity, which appears as the most important source of diversification in the electricity generation sector with regard to fuel import dependency and security of supply.

Greater fuel import dependency has different potential economic and security of supply consequences in the short- and long-term. A partial or complete sudden gas supply disruption would affect differently a gas importing country economy depending on the length of the interruption. Besides, the potential benefits of fuel mix diversity hinge on the practical feasibility of fuel mix diversification. Most electricity infrastructure is long lived, such that in the short-term, a utility is limited to selecting power sources from its existing portfolio of generating facilities and third-party power purchases. In the long-term, the utility would contemplate what fuels it would burn in new power plants or what fuels are contained in future power purchases. The next sections examine accordingly the feasibility and potential benefits of greater fuel mix diversity under two different time scales: in the short term, through improved system resilience to sudden supply disruptions, and in the long term, through a lower macroeconomic impact of high or volatile fossil fuel prices.

2.1 Diversity and resilience to supply shocks

In the short-term, a more diverse electricity generation system is likely to be less affected by fuel supply disruptions, because of its greater ability to switch fuels. Fuel-mix diversity is believed to provide a hedge against any shock that could render some fuel suddenly unavailable or extremely expensive. In particular, relying on imports for gas exposes countries to any disruptive event either in the exporting countries, or on the transit routes of the fuel. The diversity of the fuel mix is a multi-faceted issue: not only does the primary choice of fuels matter, but also the geographical source of the fuel imports, as well as the transit routes of such fuel imports. Such considerations have a critical impact on the relationship between fuel mix diversity and security of supply. While coal can be bought on a global market, gas production and reserves are concentrated in a few regions – mainly Russia and North African countries for gas imported in the EU (IEA, 2006).

Besides, while coal can be shipped easily, gas is mainly imported by pipelines through a few critical transit routes which are vulnerable to political instability or terrorist actions in the transit countries. In this perspective, the expected development of a global liquefied natural gas market (LNG) could greatly contribute to diversifying the transit supply risks associated with gas.

Energy price elasticities are generally much higher in the long term than the short term, and vary largely by fuel and region. Price elasticities are particularly low for transport fuels, as few practical substitutes are yet available for oil-based fuels for cars and trucks. In a recent study, the International Energy Agency estimates that the weighted average crude oil price elasticity of total oil demand across all regions is -0.03 in the short term and -0.15 in the long term (IEA, 2006). Similarly, demand for electricity is highly price-inelastic, with estimates ranging from -0.01 to -0.14 in the long term and even lower in the short term (IEA, 2006). Different fuels – gas, coal and oil products – can provide non-electricity stationary services (such as fuel for heating boilers), so demand for these fuels in these sectors is generally more sensitive to changes in price, especially where multi-firing equipment is widespread. Power generators may also be able to switch more quickly to cheaper fuels if they have dual-firing capability or reserve capacity.

Much debate remains, however, as regard to the link between energy-dependency and security of supply. The threats to energy security are more subtle and varied than portrayed in the crude expression of concerns about import dependence (Grubb et al., 2006). Counter arguments include the co-dependence of importers and exporters, and the nature of international markets as reasons not to fear over dependency-related threats. Bohi and Toman (1993) provide a detailed discussion of the conceptual arguments and empirical evidence related to the potential sources of market failure for energy security. There are many possible sources of interruption to supply: from unreliable political sources, from disruptions to transit routes and facilities, and even from the possibility of stalled European energy market liberalisation. Grubb et al. (2006) emphasise for instance that the major interruptions of the UK energy system in the past three decades have arisen from miners' strikes, domestic fuel blockades, and occasional power cuts – not from foreign supply disruptions.

In short, diversity helps manage the risks that are associated with individual energy technologies or sources, but diversity is not a necessary characteristic of a secure system. For instance, the French electricity supply system, based on nuclear energy, is little diversified: there is a strong focus on one fuel, one technology, and a small number of related designs. In some respects it is very secure, being robust to external political events and economic changes. In other respects it could be argued to be insecure to generic technical faults, terrorist threats or a serious nuclear accident. At the other extreme, the old UK coal-based system was also apparently secure, based on indigenous coal and a limited number of technologies. Because of its exposure to the action of trade unions, it was a non-diversified system, with a single vulnerability that turned out to be critical.

2.2 Diversity reduces the macroeconomic sensitivity to oil and gas prices

The growing share of gas-fired generation after liberalisation in many electricity markets has raised concerns over the adverse macroeconomic effects of the decrease of fuel-mix diversity and greater gas imports for gas importing countries. An important question is whether increasing reliance on gas fired generation –hence greater gas import dependency for gas importing countries– will increase their economy sensitivity to the level and volatility of oil and gas prices.

For oil-importing countries, the immediate magnitude of the direct effect of a given oil-price increase on national income can be conceptualised as depending on the ratio of oil imports to GDP (IEA, 2006). This, in turn, is a function of the amount of oil consumed for a given level of national income (oil intensity) and the degree of dependence on imported oil (import dependency).[4] It also depends on the extent to which gas prices rise in response to an oil-price increase, the gas-intensity and gas-import dependency of the economy and the impact of higher prices on other forms of energy that compete with or, in the case of electricity, are generated from oil and gas. The impact of a given change in oil and gas prices on the economy is proportionally linked to the size of the shift in the terms of trade. That shift, in turn depends on energy-import intensity. The impact of a given change in energy prices on the economy is linked to the size of the shift in the terms of trade. Levels of and historical trends in intensity vary among countries and regions. Levels of and historical trends in intensity vary among countries and regions. Some regions have seen a substantial decline in oil-import intensity since the 1980s, notably Europe and the Pacific region, while import intensity has risen in some developing countries, including China and India (IEA, 2006).

As Awerbuch and Sauter (2006) note, a large body of academic literature surveyed suggests that oil price increases and volatility dampen macroeconomic growth by raising inflation and unemployment and depressing the value of financial and other assets in oil consuming nations. The so-called ‘oil-GDP relationship’ has been statistically studied since the late 1940s (Awerbuch and Sauter, 2006, Greene and Tishchishyna, 2000).[5] The impact of oil price movements on economic growth depend largely upon the country considered. The quantitative relationship between oil price changes and economic activity and inflation can be decomposed as follows (IEA, 2004):

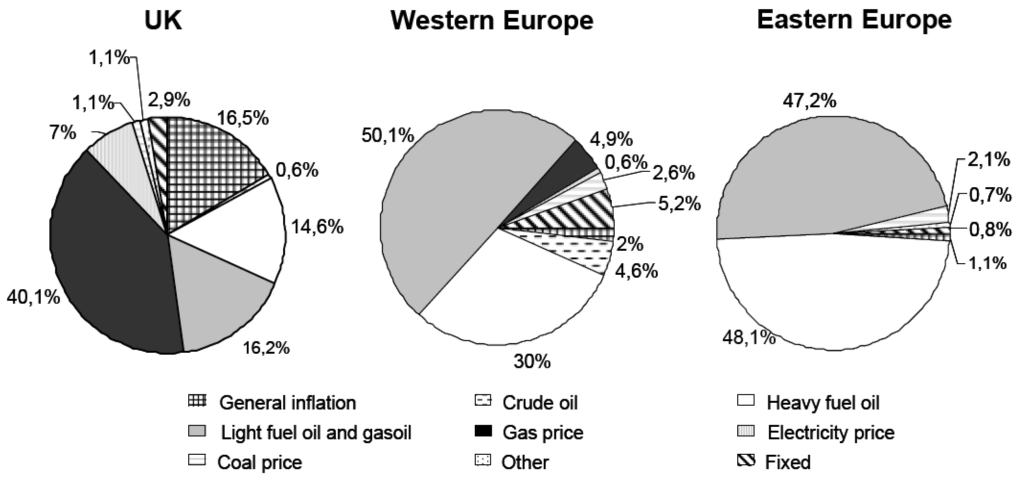
- *Terms of trade effects:* the first, and principal, impact of oil price shifts on activity arises from changes in purchasing power between oil-importing and oil-exporting nations.
- *Effect on domestic prices and inflation:* whether the increase in the price level translates into a shift in core inflation depends on the “second round” effects - *i.e.* whether workers and/or enterprises are able to compensate for the income loss through higher wages and prices -- which, in turn, depends on the monetary policy regime in place.
- *Domestic demand effects:* since oil is an input into many goods both consumers and producers would bear losses.
- *Supply-side implications: impact on output and employment.* The impact on output and employment is determined by the relative supply responses of labour and capital.
- *Longer-term outcomes:* The negative impact of an oil price rise on domestic demand and income will diminish over time as consumers and producers modify their behaviour. However, research indicates that there is an asymmetric effect, insofar as oil demand does not revert to its initial level as oil prices fall. In that case, the income losses experienced by energy importers may eventually be partly reversed. Where fluctuations in oil prices create uncertainty, there may be a reduction in trend investment activity, but it is less clear that the effects on profitability or capacity utilisation are asymmetric (Gately and Huntington, 2002, Awerbuch and Sauter, 2006).

[4] Oil import intensity (net oil imports/GDP) = import dependency (net oil imports/total oil use)*oil intensity ((total oil use/total energy use)*(total energy use/GDP)).

[5] IEA (2004) notices, however, that the negative correlation between oil prices and macro economic indicators seems to have substantially weakened over time. It gives three main reasons: first, the weight of oil and oil products in domestic production has dropped, so that terms of trade shifts are less important. Second, the wage formation process has become less responsive to fluctuations in oil prices. Third, heightened competition has helped to reduce the secondary impact on core inflation from changes in oil prices.

While the mechanism by which oil prices affect economic performance is generally well understood, the precise dynamics and magnitude of these effects – especially the adjustments to the shift in the terms of trade – are very uncertain (IEA, 2006). Quantitative estimates of the overall macroeconomic damage caused to the economies of oil-importing countries by the oil-price shocks of 1973-1974, 1979-1980 and 1990-1991, as well as the gains from the 1986 price collapse, vary substantially. This is partly due to differences in the models used to examine the issue, reflecting the difficulty of capturing all the interacting effects. For the same reason, the results of models used to predict the impact of an increase of oil prices on the GDP vary largely.[6] IEA (2006) estimates, as a rule of thumb, that the impact of a sustained $10 per barrel oil price increase would now cut average real GDP by around 0.3% in the OECD and by about 0.5% in non-OECD countries. Awerbuch and Sauter (2006) point out that the oil-GDP effect has significant ramifications for policies reducing fuel import dependency, such as increasing fuel mix diversity (through e.g. greater use of renewable or nuclear energies) and demand side energy efficiency and flexibility (through e.g. greater fuel switching possibilities). These policies mitigate exposure to fossil fuel risk and therefore help nations avoid costly economic losses; these arguments will be discussed further in the section four of this paper.

Figure 1 – Indexation of long term gas supply contracts by origin of the purchasing company Source: EC (2005)



Turning now to the impact of gas prices level and volatility on the economy, it is important to note that the price of gas tends to be highly correlated with international oil prices. This is because of both explicit price indexation and inter-fuel competition at the burner tip. The EC Sector Inquiry looked at the indexation according to the region of the purchasing company (EC, 2005).[7] Figure 1

[6] See, for example, Barrell and Pomerantz (2004), IMF (2005), Hamilton (2005), and Hunt, Lisard and Laxton (2002).

[7] The results of the EU Inquiry are based on analysis of long term purchase agreements (i.e. over 12 months) of thirty major producers and wholesalers of gas. The analysis is based on data for calendar year 2004 and indicates the average volume weighted indexation found in the sample of over 500 long term contracts, representing around 400 billion cubic metres of contracted gas. These contracts include those between companies exporting gas to Europe and major EU gas wholesalers, as well as contracts between different EU gas wholesalers.

shows the indexation of long-term gas supply contracts depending on whether the buyer was from the UK, Western Europe or Eastern Europe.[8] Interestingly, the indexation present in long-term contracts for gas supply to continental Europe is very different to that found in the UK, where over 40% of the price volatility of gas under long-term contracts is determined by changes to the actual hub price of gas (usually the NBP or IPE prices). For Western Europe, changes in hub gas prices only account for around 5% of indexation. Conversely, the importance of heavy fuel oil and light fuel oil to determine the price level paid under long-term contracts is much higher in Western Europe (over 80% of indexation) and Eastern Europe (around 95% of indexation), than in the UK (around 30% of indexation).

Even in North America and Britain, where most contracts no longer include any formal links to oil prices, gas prices tend to move in line with oil prices because of fuel switching by industrial end-users and power plants (IEA, 2006). Opportunities for arbitrage with continental Europe, by LNG and, in the case of Britain, via the Bacton-Zeebrugge Interconnector, also tend to make oil and gas prices converge.[9] This explicit price indexation and inter-fuel competition results in wholesale gas prices reflecting the developments of the oil market, and in particular the market for oil derivatives such as heavy or light fuel oil. The EC Inquiry estimates that these account for around three quarters of gas price volatility (EC, 2006). As a consequence, greater dependence on gas-fired power generation can be expected to amplify the sensitivity of the European countries economies to oil and gas price fluctuations and shocks.

3 QUANTIFYING AND VALUING THE BENEFITS OF DIVERSITY

While it seems relatively difficult to compute the macroeconomic value of diversifying the electricity generation mix, it is important to advance research in this area to provide a normative approach for policy makers. As pointed out by Costello (2005), care must indeed be taken that arguments in favour of diversity are not used opportunistically by those seeking (via political mechanisms) to protect particular firms and industries. This underlines the need to develop analytical tools to quantify the costs and benefits of increased fuel mix diversity. This section introduces various indices that can be used to quantify fuel mix diversity, and then discusses how new analytical tools borrowed from the financial literature (such that Mean Variance Portfolio Theory and Real Options theory) can be used to value the costs and benefits of generation mix diversity.

[8] The Western Europe sample consists of long-term gas supply contracts to companies in Austria, Belgium, Denmark, France, Germany, Italy and the Netherlands. The Eastern Europe sample consists of long-term gas supply contracts to companies in the Czech Republic, Hungary, Poland, Slovakia and Slovenia.

[9] Term contracts –often covering very long terms of twenty or more years – account for well over 95% of bulk gas trade in continental Europe (almost 100% outside of Belgium and The Netherlands). Almost all these contracts include oil-price indexation. In Britain, term contracts – which are generally much shorter in duration than in the rest of Europe – account for 90% of all bulk trade. In contrast to the rest of Europe, they almost always price the gas on the basis of spot or futures gas prices, usually at the Notional Balancing Point. Nonetheless, a small number of contracts may have some limited degree of oil-price indexation (IEA, 2006).

3.1 Quantifying fuel mix diversity

Stirling (1994, 1998 and 2001) pioneered research in the application of diversity concepts to the energy sector. Stirling argues that *uncertainty* and *ignorance,* rather than *risk*, dominate real electricity investment decisions and conceptualizes *diversification* as a response to these more intractable knowledge-deficiencies. In addition to difficulties in definitely characterising or partitioning the possibilities, there is a prospect of unexpected outcomes, arising entirely outside the domain of prior possibilities.[10] Stirling (1998) shows that diversity can be considered from different angles, notably *variety* (the number of available options, categories, species), *balance* (the spread among options) and *disparity* (the nature and degree to which options are different from each other). Variety, balance and disparity constitute "three necessary but individually insufficient conditions for diversity" (Stirling 1998). He however points out that inclusion of disparity remains cumbersome, as the concept of disparity differs from variety and balance in that it is inherently qualitative.

In a seminal contribution to mathematical ecology, Hill (1973) directly addresses the fundamental issue of the trade-off between variety and balance in the measurement of diversity. Based on the characterisation of diversity in terms of 'proportional abundance', Hill (1973) identifies and orders an entire family of possible quantitative measures of diversity. Each is subject to the same general form:

$$\Delta_a = \left(\sum_{i=1}^{I} (p_i{}^a) \right)^{1/(1-a)}, \quad a \neq 1,$$
$$= \sum_{i=1}^{I} - p_i \ln(p_i), \quad a = 1.$$

where Δ_a specifies a particular index of diversity, p_i represents (in economic terms) the proportional representation of option *i* in the portfolio under scrutiny, and *a* is a parameter which effectively governs the relative weighting placed on variety and balance. The greater the value of the parameter *a*, the smaller the relative sensitivity of the resulting index to the presence of lower-contributing options.

For *a=2*, the reciprocal of the function is referred to in ecology as the *Simpson diversity index* and in economics as the *Herfindahl-Hirschman concentration index.* Assuming that p_i is the market share of the ith firm or the proportion of generation met by one particular fuel source, then the Herfindahl-Hirschman concentration index is calculated according to $\Delta_2 = \sum_{i=1}^{I} p_i^2$. The Herfindahl-Hirschman Index takes into account both the relative size and distribution of each source, increasing as the number of firms falls and the disparity in the size of those firms increases.[11]

For *a=1*, the result is the Shannon-Wiener index (Stirling, 1998). The *Shannon-Wiener Diversity Index* is the most attractive simple index reflecting both variety and balance in an even way

[10] Stirling distinguishes three basic states of incertitude:
- Risk: "a probability density function may meaningfully be defined for a range of possible outcomes"
- Uncertainty: "there exists no basis for the assignment of probabilities"
- Ignorance: "there exists no basis for the assignment of probabilities to outcomes, nor knowledge about many of the possible outcomes themselves…"

[11] The maximum value of the index is 10000 in the case of a monopoly, falling towards zero as the market moves towards a situation of perfect competition.

(Stirling, 1998). The reasons are that this index is insensitive to final ordering (changes of the base of logarithms do not change the rank orderings of different system) and is additive in case of a refining of the taxonomy (the index value for a system of options, which has been disaggregated according to a combined taxonomy, should be equal to the sum of the index values obtained for the same system classified under each taxonomy individually). The higher the value taken by the index, the more diverse is the system.

An intuitive rationale for the use of the Shannon-Wiener function as an index of electricity supply system security is to think of it as a measure of the probability that a hypothetical unit of electricity sampled from the system at random has been generated by any particular option. The more diverse the system, the greater will be the uncertainty over which option will have generated the next sampled unit of electricity. Jansen et al. (2004) elaborate on the *Shannon-Wiener Diversity index* to design a macro indicator for long-run energy supply security. Four long-term energy security indices are presented, allowing for an increasing number of long-term supply security aspects, and then applied to reference year 2030 of four long-term sustainability outlook scenarios. Aspects introduced in their indicators on a stepwise additional basis are successively:

- Diversification of energy sources in energy supply. This corresponds to the basic *Shannon-Wiener Diversity index.*
- Diversification of imports with respect to imported energy source. This second indicator provides for an adjustment of the basic indicator for the net import dependency.
- Long-term political stability in import regions. The third additional adjustment to the indicator accounts for the level of long-term political stability in regions of origin, using the UNDP Human Development Indicator as index for long-term socio-economic stability.
- Allowance for resource depletion. The fourth indicator allows for the level of resource depletion on an additional basis.

3.2 From quantification to valuation of fuel mix diversity

While Stirling's (1994, 1998, 2001) pioneering work on diversity indexes greatly contributed to defining the diversity of an electricity system, it does not inform the question as to *how much* diversity is needed.[12] The extent to which diversity is to be pursued depends on the balance between the extra costs and the degree of risk reduction achieved. Fuel diversity should not be perceived as an end, but only as a means that has the capability to generate benefits less costly than other alternatives in achieving the same objectives. For example, financial instruments may have lower costs than fuel diversity, which can be viewed as a physical hedge in reducing price risk to a tolerable level. Fuel diversity may also create costs from the loss of scale economies associated with traditional generation technologies, and from owing and operating a portfolio of power sources that include several fuels and technologies, some of which may not have the lowest expected costs.

The diversity indexes presented before do not exploit statistical information. Thinking about fuel mix diversity in terms of risk, e.g. price risk for fossil fuel supplies, one can make use of other analytical approaches using statistical data to identify the optimal degree of diversity of an

[12] See also Lucas et al. (1995) for a critic of Stirling's diversity index.

electricity system, by trading off the degree of risk reduction achieved by diversifying away from gas-fired generation against the extra cost of doing so. As argued by Awerbuch and Berger (2003), such approaches rely on the assumption that while these precise outcomes may never be perfectly repeated in the future, they at least provide a guide to the future.[13] The strength of such approaches rests on the presumption that the past is a reliable guide to the future. This is not to say that unexpected events will not happen – only that the effect of these events are already known from past experience (Awerbuch and Berger, 2003).

Fuel mix diversity provides a hedge against potential price shocks affecting one type of fuel, e.g. imported gas, or supply shocks due to physical disruption in the supply chain. Investing in generation technologies which help a country (or a utility) to mitigate its exposure to fossil fuel supply disruptions or price risks can be thought as an *insurance*. Calculating the value associated with such insurance requires a different approach from the traditional static valuations of the "least cost option" on a stand alone basis (see e.g. Roques et al., 2006a, for a critic of the traditional levelised cost methodology). Power generation investment valuations need to capture both the *portfolio effects* – the complementarity of one additional unit with the existing portfolio of plants of a country or utility – and the *option value effects* arising out of uncertainties in fossil fuel prices and volatility – e.g. the option value of operating renewables and nuclear plants in case gas prices increase. In other words, identifying the optimal degree of fuel mix diversity for a country or utility requires valuation approaches of power generation investments which trade off the risks and returns of increased portfolio diversification, both in a *static* and *dynamic* perspective. The following subsections introduce successively static (Value-at-Risk and Portfolio theory) and dynamic approaches (Real Options) to value fuel mix diversity.

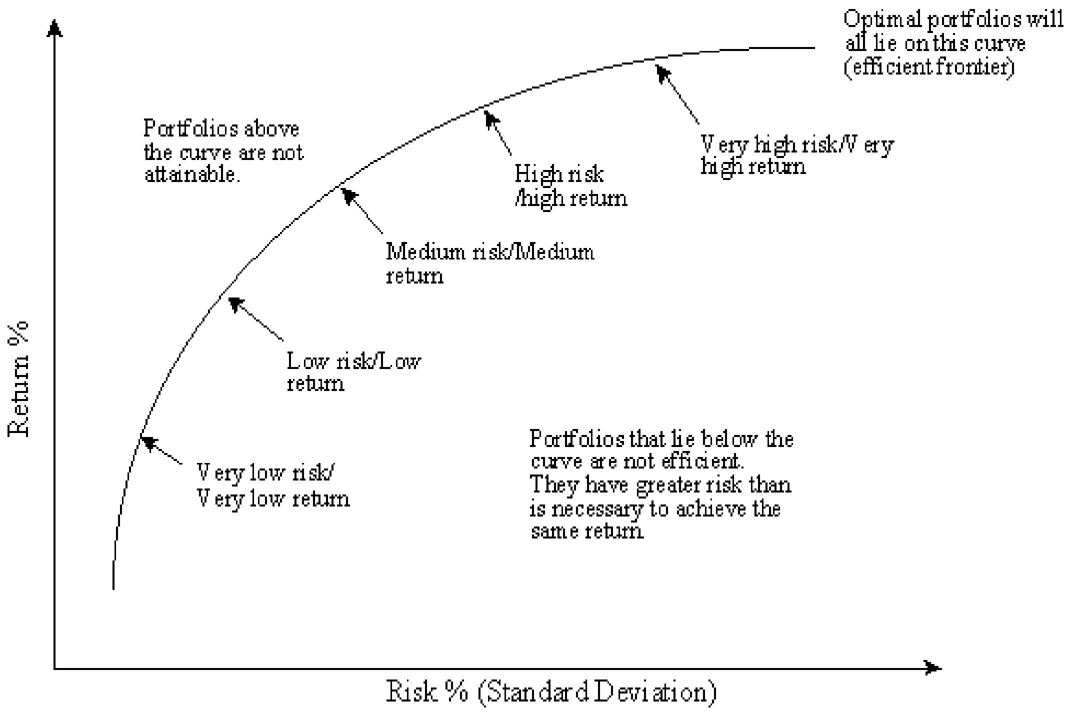
3.2.1 Mean-Variance Portfolio Theory

The *Value-at-Risk* (VaR) approach gained increasing popularity in banking and assets and liabilities management applications by the end of the 1990s.[14] The Value-at-Risk calculates the maximum loss expected (or worst case scenario) on an investment, over a given time period and given a specified degree of confidence (Brealey and Myers, 2000). The VaR approach can be applied to any portfolio of assets and liabilities, whose market values are available on a periodic basis. Typically, normal distributions are assumed with values for price volatility, based on past statistics. Using calculated parameter values for the whole portfolio, the maximum portfolio loss can be projected provided a specific unlikely event does not occur, for example a 5% chance of an adverse price movement within the next holding period. However, to implement it, the probability distribution of price changes for each portfolio instrument should be known, and the VaR approach depends critically on reasonable estimates of price volatility and correlations among financial assets, as well as the assumed distribution of price changes. Kleindorfer and Li (2005) provide a recent review of progress in the VaR theoretical literature, and apply it to characterize multi-period VaR-constrained portfolios of real and contractual assets in the power sector.

[13] While no particular random event may ever be precisely duplicated, nonetheless, historic variability is widely considered to be a useful indicator of future volatility (e.g. in the case of equity stocks).
[14] VaR is based on the common-sense fact that for investors, risk is about the odds of losing money. By assuming investors care about the odds of a big loss, VaR addresses one of the main issues with the traditional measure of risk, volatility. The main problem with volatility, indeed, is that it does not address the direction of an investment's movement: a stock can be volatile because it suddenly jumps higher. But investors are not distressed by gains.

Another probabilistic approach to value and optimise fuel mix diversity is Markowitz's *Mean-Variance Portfolio theory* (Markowitz, 1952).[15] Mean-variance portfolio theory (hereafter MVP) defines portfolio risk as *total risk* - the sum of random and systematic fluctuations - measured as the standard deviation of periodic historic returns.[16] An efficient portfolio is one which has the smallest attainable portfolio risk for a given level of expected return (or the largest expected return for a given level of risk). The process for establishing an optimal (or efficient) portfolio generally uses historical measures for returns, risk (standard deviation), and the correlation coefficients between the different assets to be used in the portfolio.

Figure 3 - Efficient frontier for a portfolio of 2 risky assets



By computer processing the returns, risk (standard deviation of returns) and correlation coefficients data, it is possible to establish a number of portfolios for varying levels of return, each having the least amount of risk achievable from the asset classes included. These are known as optimal portfolios, which lie on the *efficient frontier*. Figure 3 shows the efficient frontier for a portfolio of two risky assets. The graph visualizes the set of optimal portfolios. Optimality refers to Pareto optimality in the trade-off between portfolio risk and portfolio return. For each portfolio on the efficient frontier:

- The expected portfolio holding period return (HPR) cannot be improved without increasing expected portfolio HPR risk.
- The expected portfolio HPR risk cannot be reduced without reducing expected portfolio HPR.

[15] See e.g. Fabozzi et al. (2002) for a recent review of the developments of Portfolio theory

[16] Modern portfolio theory makes some assumptions about investors. It assumes they dislike risk and like returns, will act rationally in making decisions and make decisions based on maximising their return for the level of risk that is acceptable for them. When making asset allocation decisions based on asset classes it is assumed that each asset class is diversified sufficiently to eliminate specific or non-market risk.

The investor then simply has to choose which level of risk is appropriate for their particular circumstances (or preference) and allocate their portfolio accordingly. In other words, MVP theory does not prescribe a single optimal portfolio combination, but a range of efficient choices. Investors will choose a risk-return combination based on their own preferences and risk aversion.

Mean-Variance Portfolio (MVP) theory, initially developed for financial securities, can be applied to generation assets to determine the optimal portfolio for a country or generation company. MVP theory makes assumptions on the assets considered and investors' behaviour (such as risk aversion), which are discussed in detail in Awerbuch and Berger (2003) and Roques et al. (2008) in the context of investment in electricity markets. As Awerbuch and Berger (2003, page 5) observe, "the important implication of portfolio-based analysis is that the relative value of generating assets must be determined not by evaluating alternative assets, but by evaluating alternative asset portfolios. Energy planning therefore needs to focus less on finding the single lowest cost alternative and more on developing efficient (i.e. optimal) generating portfolios".

Bar-Lev and Katz (1976) pioneered the application of MVP theory to fossil fuel procurement in the U.S. electricity industry. By applying an MVP approach on a regional basis, they determined the theoretical efficient frontier of fossil fuel mix for various regulated utilities and compared it to the actual experience of the electric utilities. Bar-Lev and Katz (1976) showed that generally the electric utilities efficiently diversified, but that their portfolios were generally characterised by a relatively high rate of return and risk, which they interpreted as being a consequence of the 'cost-plus' regulatory regime encouraging utilities to behave in a risky way. Humphreys and McClain (1998) use MVP theory to demonstrate how the energy mix in the U.S. could be chosen given a national goal to reduce the risks to the domestic macro economy of unanticipated energy price shocks. They note that the electric utility industry has moved towards more efficient points of production since the 1980s, and that the switch towards natural gas in the 1990s might be driven by the desire for higher returns to energy investment in the industry.

Awerbuch (2000) evaluates the U.S. gas-coal generation mix and shows that adding wind, photovoltaics, and other fixed-cost renewables to a portfolio of conventional generating assets serves to reduce overall portfolio cost and risk, even through their stand-alone generating costs may be higher. Awerbuch and Berger (2003) use MVP to identify the optimal European technology mix, considering not only fuel price risk but also O&M, as well as construction period risks. Awerbuch and Berger (2003) find that compared to the EU-2000 generation mix, the projected EU-2010 mix exhibits a higher risk coupled with higher return. Moreover, the projected EU-2010 mix does not lie on the efficient frontier, though it comes close, indicating that better portfolios exist. These would likely include higher shares of old coal along with a higher share of wind.[17] Jansen et al. (2006) uses portfolio theory to explore the risk and returns of various portfolio mixes corresponding to different scenarios of the electricity system development in the Netherlands. The general conclusion of the Portfolios theory applications to valuing diversity based on production costs and concentrating on fuel price uncertainty, i.e. taking a national or societal perspective, is that more diverse generation portfolios are in general associated with lower risks for the same returns. In particular, optimal portfolios contain a substantial share of fixed-costs (when considering only fuel price uncertainty) renewables and nuclear, whose costs have a low covariance with the production costs of fossil fuel technologies.

[17] Note that this study does not account for the cost of CO_2 emission permits in the European Trading Scheme.

Roques et al. (2008) applies portfolio theory to identify optimal portfolios for electricity generators in the UK electricity market, concentrating on profit risk rather than production costs risk. In such a private investor perspective, electricity price risk (and in Europe CO_2 price risk) is also relevant for determining optimal portfolios, and in particular the covariance of electricity, fuel, and CO_2 prices. Roques et al. (2008) concludes that in the absence of long-term power purchase agreements, optimal portfolios for a private investor differ substantially from socially optimal portfolios, as there is little diversification value for a private investor in a portfolio of mixed technologies, because of the high empirical correlation between electricity, gas, and carbon prices. Moreover, Roques et al. (2008)'s results suggest that the current UK industry framework is unlikely to reward fuel mix diversification sufficiently so as to lead private investors' technology choices to be aligned with the socially optimal fuel-mix, unless investors can find counter parties with complementary risk profiles to sign long-term power purchase agreements. These findings raise questions as to whether and how policy makers or regulators should modify the market framework, given the macroeconomic and security of supply benefits of a diverse fuel-mix. Roques et al. (2008)'s model results suggest in particular that alternative institutional risk allocation mechanisms (e.g. long-term power purchase contracts) might render capital intensive but fuel-price risk free technologies such as nuclear power or renewables more attractive to investors - and thereby provide power companies with stronger incentives for fuel mix diversification.

3.2.2 Dynamic valuation approaches: the option value of diversity

Another concept borrowed from the finance literature, called *Real Options*, can be applied to supplement the information provided by static discounted cash flow analysis. In its simplest terms, *Real Options* theory says that when the future is uncertain, it pays to have a broad range of options available and to maintain the flexibility to exercise those options. Real Options theory has pointed to the shortcomings of the static valuation approaches for inputting a value on the ability of a utility to dynamically react to changing market and other conditions. Specifically, static approaches can understate, if not ignore, *managerial flexibility*. *Real options* valuation allows for adjustment of the *timing* of the investment decision. It is therefore particularly well suited to evaluate investments with uncertain payoffs and costs, as it can capture the option value contained in managerial flexibility in the face of future uncertain developments: the greater the uncertainty that can be resolved, the more advantageous it is to wait and thus the higher the option value (Dixit and Pindyck, 1994, Trigeorgis, 1996).

Real options theory can be applied to analyse the economics of renewable energy or nuclear power versus fossil fuel generation technologies when fuel prices and/or electricity prices are uncertain.[18] There are potentially two attributes of non fossil-fuel technologies such as renewables and nuclear power generation that could improve their value to society or investors in a dynamic perspective. First, production costs of such technologies are insensitive to both gas and carbon prices.[19] Therefore, rising gas prices and carbon trading or carbon taxes will make nuclear and renewables more competitive against CCGTs and coal-fired plants. Second, investing in non fossil-fuel

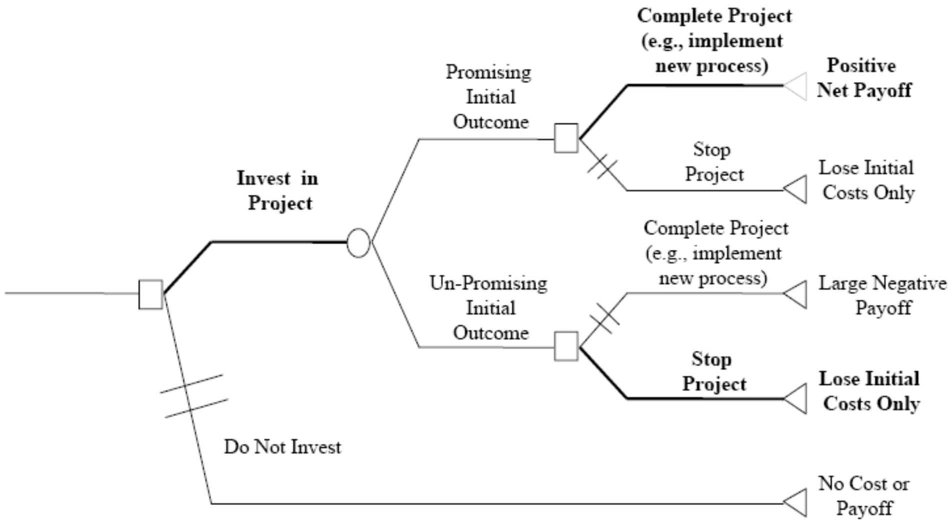
[18] Quantifying the option value requires, however, restrictive assumptions on the stochastic behaviour of the electricity and natural gas market prices, and to rely on data from relatively illiquid forward markets. See Frayer and Uludere (2001) for a description of the limits of applying Real options analysis to power investments.

[19] Nuclear fuel price have relatively little effect on electricity generation costs: a doubling of the uranium oxide price would increase the fuel cost for a light water reactor by 30%, and the electricity cost by only about 7%, whereas doubling the gas price would add 70% to the price of electricity.

technologies can be thought as a hedge against the volatility and risk of gas, coal and carbon prices for a country or a (large) generating company. The uncertainty over the evolution of gas and carbon prices implies that there is an option value associated with being able to choose between non fossil-fuel generation technologies and fossil fuel technologies in the future.

Real Option theory can therefore rationalise embarking upon a power-plant project that is not expected to be economical for a period of years but offers the possibility of benefits in the longer term. For instance, Murto and Nese (2002) compare natural gas fired plant economics with biomass plants and show that natural gas price uncertainty considerably improves the competitiveness of the biomass plant, when taking into account the option value associated with input cost uncertainty. Roques et al. (2006c) compute the option value to a company of the ability to choose between a nuclear and a gas-fired plant investment at successive moments in the future, when the company faces stochastic gas, carbon, and electricity prices. They show that this option value depends sensitively on the degree of correlation between electricity, gas, and carbon prices, and conclude that there is little private company value in retaining the option to choose between nuclear and CCGT technologies in future in liberalised European electricity markets, which exhibit a strong correlation between electricity, gas and carbon prices.

Figure 4: Example of Project Involving An Option: the initial decision to do R&D provides the Option to Invest in Completing Development, for instance by building a plant.



Real Options analysis can also be applied to other benefits associated with of a more diverse electricity generation system, as the value of real options is closely linked to the benefits of having more flexibility. The concept can for instance apply to whether a utility should buy a new power plant or purchase power. An illustration of a failure to retain an option would be where a utility signs a long-term purchased power contract with rigid take and price provisions (Costello, 2005). If subsequent to the signing of the contract the market price of electricity plummeted or expected load growth failed to materialize, or both, the utility could suffer large contractual liability. Real options theory could also justify staggering the timing of capital expenditures for new generation facilities under uncertainty, committing to new construction in stages.[20] By waiting for new information, and in the meantime initiating development of promising technologies (for example, on a pilot or demonstration basis), the utility would have more flexibility in adapting to the new conditions as they unfold.

Another application of interest of Real Option modelling concerns the valuation of research, development, demonstration and deployment (RDDD) programs of new power generation technologies. Cost benefit analysis of such publicly funded programs typically employs a deterministic forecast of the cost and performance of renewable and non-renewable fuels which ignores uncertainty in the cost of non-renewable energy, the possibility of adjustment to the RDDD effort commensurate with the evolving state of the world, and the underlying technical risk associated with RDDD. Siddiqui et al. (2006) find that the total option value of renewable energies is dominated by the value of existing renewable technologies, while the value of enhancements to renewables technologies from future RDDD is a modest 10% of the total, and the value of the abandonment option is insignificant. Davis and Owens (2003) use a similar Real Options approach to estimate the value of the US renewable electric technologies R&D program in the face of uncertain fossil fuel prices. They estimate the current value of expected future supply from renewable electric technologies, net of federal R&D expenditures, at $30.6 billion (in 2000 dollars).[21] While these two models' estimates of renewable technologies option value are sensitive to the selected parameters values, which are subject to debate, Siddiqui et al. (2006) and Davis and Owens (2003) results demosntrate that renewable technologies hold a significant amount of value that cannot be detected by using traditional static valuation techniques.

4 CONCLUSIONS

This paper discussed potential adverse consequences of a power generation mix dominated by gas fired power plants in terms of security of supply and macroeconomic resilience to oil and gas prices movements. This paper argued that greater diversity generally enhances the robustness of an electricity system to fossil fuel supply shocks, and hence yields macroeconomics and security of supply benefits. However, this paper pointed out that while diversity can be seen as a desirable feature of an electricity system, it is not a necessary condition. Perhaps more importantly, it is not clear *what* should be diversified, and *how much* diversity is optimal. Because the generation mix diversity is a multi-faceted issue, it is indeed difficult to quantify the costs and benefits associated with greater fuel mix diversity.

New analytical tools borrowed from the financial literature are powerful analytical tools to value the costs and benefits of reducing some risks. These include *static* valuation methods such as Portfolio theory, and *dynamic* valuation methods such as Real Options which take into account the option value of diversity as a hedge against potential fossil fuel supply or price shocks. Findings of recent studies using such analytical approaches to value diversity were discussed, showing that

[20] Gollier et al. (2005) compare the benefit of a large nuclear power plant project coming from increasing returns to scale, to the benefit of a modular sequence of smaller, modular, nuclear power plants on the same site. They show that under price uncertainty only, the benefit of modularity is equivalent in terms of profitability to a reduction of the cost of electricity by one-thousand of a Euro per kWh.

[21] The model assumes a current ratio of renewables to non renewables electricity generating costs of 1.29, and a 1 to 4% annual rate of decline of renewables technologies generating costs, depending on the level of R&D funding. The cash flows of renewable and non renewable technologies are discounted using the risk free interest rate.

non-fossil fuel technologies have a significant 'hedging value' from a societal perspective vis-à-vis fuel and CO_2 price risks. Valuation approaches can therefore rationalise embarking upon a power-plant project that is not expected to be economical for a period of years but offers the possibility of benefits in the longer term. Most importantly, contrasting the societal value of diversity with the results from studies quantifying the value of fuel mix diversity to *private* investors casts doubt as to whether the current liberalised market framework provides adequate diversification incentives.

This paper serves as an introduction to a book providing a selection of the recent research applying Mean-Variance Portfolio theory to optimize fuel mix diversity and security in liberalised power markets (Bazilian and Roques, 2008).

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