

# *IEA/EET Working Paper*

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## **APPLYING PORTFOLIO THEORY TO EU ELECTRICITY PLANNING AND POLICY-MAKING**

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**OVERVIEW OF THIS REPORT**

This study, co-authored by Shimon Awerbuch and Martin Berger, introduces mean-variance portfolio theory and evaluates its potential application to the development of efficient (optimal) European Union (EU-15) generating portfolios that enhance energy security and diversification objectives. The analysis extends to European countries the previous work done by Awerbuch in the US, and applies a significantly more detailed portfolio model that reflects the risk of the relevant generating cost streams: fuel, operation and maintenance (O&M) and construction period costs. It illustrates the portfolio effects of different generating mixes. The study offers preliminary findings on the effects of including more renewable energy sources in the typical EU portfolio mix and suggests interesting directions for further study.

The study arises from the perception that these standard, finance-oriented analyses may offer valuable enhancements to energy planning, and concepts of energy security and diversity. Clearly the combination of better portfolio construction and more accurate pricing should lead to more optimal decisions in the round. This study, therefore, represents an effort to complement traditional approaches and point researchers and planners into new territory.

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## APPLYING PORTFOLIO THEORY TO EU ELECTRICITY PLANNING AND POLICY-MAKING

### 1.1 Introduction

Portfolio analysis is widely used by financial investors to create robust portfolios that produce efficient outcomes under various economic conditions. In essence, an efficient portfolio takes no unnecessary risk relative to its expected return. Put another way, efficient portfolios are defined by the following properties: they maximise the expected return for any given level of risk, while minimising risk for every given level of expected return.

In the case of energy policy, portfolio-based techniques can suggest ways to develop diversified generating portfolios with known risk levels that are commensurate with their expected overall electricity generation costs. Simply put, the underlying insight is that efficient generating portfolios can minimise society's energy price risk.

Energy security considerations<sup>1</sup> are generally focused on the threat of abrupt supply disruptions, although a case can also be made for the inclusion of a second aspect: the risk of unexpected electricity cost increases. This is a subtler, but equally crucial, aspect of energy security. Energy security is reduced when countries (and individual firms) hold inefficient portfolios that are needlessly exposed to cost risk.

A growing body of literature now indicates that fossil price fluctuations depress economic activity in fossil fuel-importing nations. Even small percentage increases in fossil prices can yield sizeable economic losses through unemployment and lost income, as well as the loss of value for financial and other assets.<sup>2</sup> Efficient generating portfolios minimise national exposure to such fluctuations, commensurate with creating optimal overall generating costs. Efficient generating portfolios expose society to the minimum level of risk needed to attain given energy cost objectives.

Traditional energy planning in the US and Europe focuses on finding the least cost generating alternative, although in today's dynamic environment it is probably impossible correctly to identify the 30-year "least cost" option. Least cost procedures are roughly analogous to trying to identify

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<sup>1</sup> See e.g. Green Paper "Towards a European strategy for the security of energy supply" (European Community 2001).

<sup>2</sup> Given the estimates in this literature, such economic losses can run to the tens, even hundreds, of billions of US dollars: see Sauter and Awerbuch (2002). For an excellent recent survey of this literature see: Papapetrou (2001); see also Sadorsky (1999), Yang, et al. (2002), and Ferderer (1996).

yesterday's single best performing stock and investing in it exclusively for the next 30 years [Awerbuch 2000a]. Clearly, modern finance theory offers better tools.

Energy planning is not unlike investing in financial securities, where financial portfolios are widely used by investors to manage risk and to maximize performance under a variety of unpredictable outcomes. Similarly, it is important to conceive of electricity generation not in terms of the cost of a particular technology today, but in terms of its portfolio cost. At any given time, some alternatives in the portfolio may have high costs while others have lower costs, yet over time, an astute combination of alternatives can serve to minimize overall generation cost relative to the risk.

Energy planning needs to focus less on finding the single lowest cost alternative and more on developing efficient (i.e. optimal) generating portfolios. Indeed, modern finance theory would counsel us to evaluate the relative cost of conventional and renewable energy sources not on the basis of their stand-alone cost, but on the basis of their portfolio cost — i.e. their cost contribution relative to their risk contribution to a portfolio of generating resources. More precisely, the relevant portfolio measure for valuing generating options is how a particular option affects the generating costs of the portfolio of resource options relative to how it affects the risk of that portfolio.

Along these lines, it can be shown (Awerbuch, 2000, 1995b) that adding wind, PV 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. The important implication of portfolio-based analysis is that the relative value of generating assets must be determined not by evaluating alternative resources, but by evaluating alternative resource portfolios.

This analysis focuses on the EU and makes some substantial enhancements to a portfolio model first used by Awerbuch to evaluate the US gas-coal generation mix [Awerbuch (2000), Awerbuch (1995b)]. That model considered only fuel price risk of two technologies, on the presumption that for fossil technologies fuel costs dominate other cost categories and therefore provide a reasonable mean-variance proxy. The current model, by contrast, appropriately defines fuel, O&M, as well as construction period risk on the basis of the historic standard deviation (SD) of their "holding period" returns and their interrelationship (covariance) with other costs. In addition, the current model handles a full complement of technologies including gas, coal, nuclear, oil and a "bundle" of renewables represented in this analysis by wind technology.

### Portfolio basics <sup>3</sup>

Portfolio selection is generally based on mean-variance portfolio theory developed by Harry Markowitz (1952). It enables the creation of minimum-variance portfolios for any given level of expected (mean) return. Such efficient portfolios therefore minimise risk, as measured by the standard deviation (SD) of periodic returns.<sup>4</sup> The idea is that while investments are unpredictable and risky, the co-movement or covariance of returns from individual assets can be used to help insulate portfolios, thus creating higher returns with little or no additional risk.

Portfolio theory was initially conceived in the context of financial portfolios, where it relates  $E(r_p)$ , the expected<sup>5</sup> portfolio return, to  $\sigma_p$ , the total portfolio risk, defined as the standard deviation of past returns.<sup>6</sup> The relationship is illustrated below using a simple, two-stock portfolio. The expected portfolio return,  $E(r_p)$ , is the weighted average of the individual expected returns  $E(r_i)$  of the two securities:

$$E(r_p) = X_1 \cdot E(r_1) + X_2 \cdot E(r_2) \quad (1.1)$$

Where:

$E(r_p)$  is the expected portfolio return;

$X_1, X_2$  are the proportions (percentages) of the assets 1 and 2 in the portfolio; and

$E(r_1), E(r_2)$  are the expected returns for assets 1 and 2; specifically: the mean of all possible outcomes, weighted by the probability of occurrence; e.g.: for asset 1 it can be written:  $E(r_1) = \sum p_i r_i$  where  $p_i$  is the probability that outcome  $i$  will occur, and  $r_i$  is the return under that outcome.

Portfolio risk,  $\sigma_p$ , is also a weighted average of the two securities, but is tempered by the correlation coefficient between the two returns:

$$\sigma_p = \sqrt{X_1^2 \sigma_1^2 + X_2^2 \sigma_2^2 + 2X_1 X_2 \rho_{12} \sigma_1 \sigma_2} \quad (1.2)$$

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<sup>3</sup> Parts of this section previously appeared in Awerbuch (1995b) and Awerbuch (2000).

<sup>4</sup> The standard deviation is simply the square root of variance.

<sup>5</sup> In the case of perfect markets, expectations are assumed to be unbiased, but not error-free.

<sup>6</sup> Financial holding period return [Seitz (1990) p. 225]:  $r_t = \frac{EV_t - BV_t + CF_t}{BV_t}$  where  $EV_t$  is the ending value,  $BV_t$  the beginning value and  $CF_t$  the "cash inflow during each period  $t$ ". It is assumed that the past is a guide to the future.

Where:

$\rho_{12}$  is the correlation coefficient between the two return streams<sup>7</sup>, and

$\sigma_1$  and  $\sigma_2$  are the standard deviations of the periodic returns to asset 1 and 2 respectively.

### The portfolio effect — Risk for a two-asset portfolio

Properly designed portfolios yield a portfolio effect - risk reduction attained through diversification. Some amount of diversification occurs whenever the returns of two (or more) securities are less than perfectly correlated (i.e.  $\rho < 1.0$ ), although it is not significant where correlations are high, say on the order of +0.7 or greater.

Figure 1-1 illustrates the portfolio effect in the case of two financial assets whose returns have a correlation coefficient of  $\rho = 0.6$ . Stock A is riskier. A portfolio consisting entirely of A has an expected return of 17% coupled with a standard deviation of its historic returns of approximately 0.41. Stock B is less risky, with an expected return of about 7.2% and SD = 0.26.

Starting with a portfolio of 100% stock B, and introducing increasing amounts of A, observe that portfolio risk at first decreases<sup>8</sup> until the minimum variance portfolio is reached -- Portfolio V.

From a risk-reward perspective, it makes little sense to own only stock B, (or analogously, generating technology B) since there exist combinations of A and B that will produce superior results. In general, it makes no sense to own any portfolio combination that lies below portfolio V. For example, Portfolio R, (consisting of 48% A plus 52% B<sup>9</sup>) has the same standard deviation as Portfolio P (18% A + 82% B) but produces a higher expected return. Investors' seeking returns greater than those provided by V and R must accept greater risk by incorporating more stock A into their mix. This moves them along the risk-reward curve to portfolios like S.

Given the two risky assets A and B, it is not possible to prescribe a single optimal portfolio combination, only the range of efficient choices, i.e. those that lie on the risk-return curve above V.

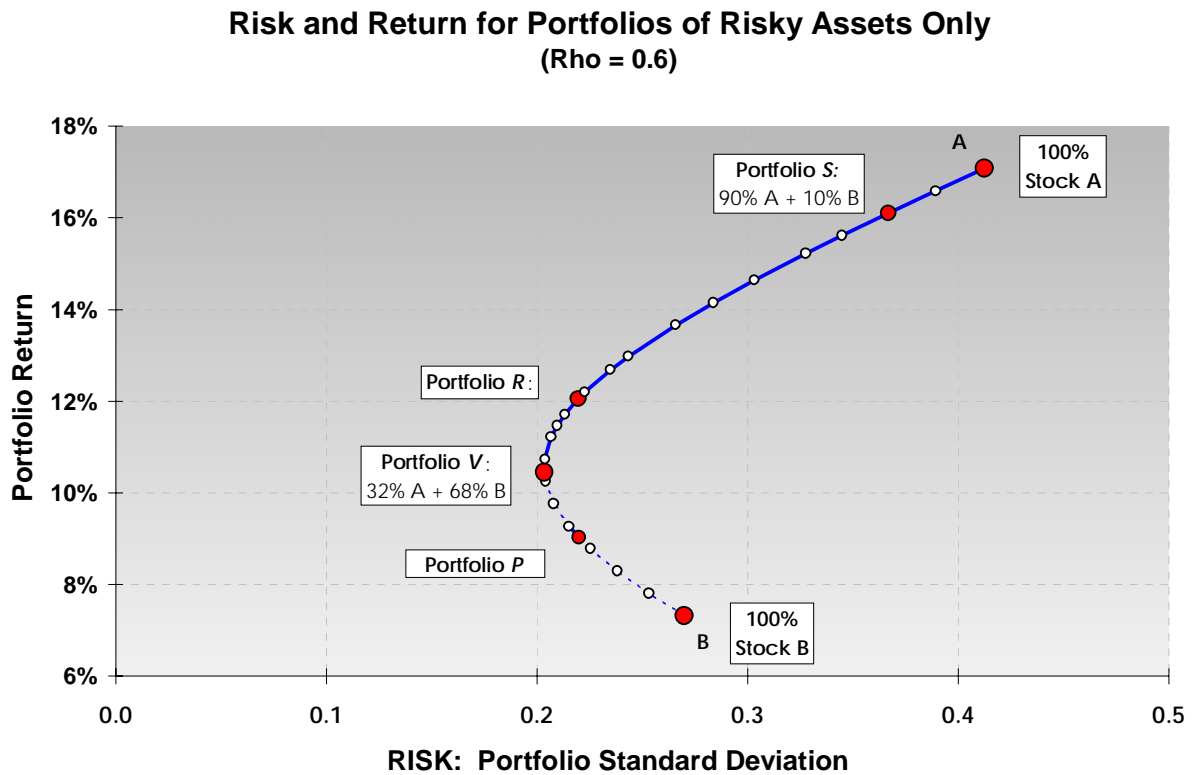
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<sup>7</sup> The covariation of two return streams can be calculated by  $COV_{12} = \rho_{12}\sigma_1\sigma_2$ . Therefore equation 1.2 might as well be written as  $\sigma_p = \sqrt{X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + 2X_1X_2COV_{12}}$ .

<sup>8</sup> This seems at first to be somewhat counter-intuitive since A has the higher risk. The initial risk reduction is driven by the correlation of the returns of these two assets, which implies that sometimes the return of one rises while the return of the second falls. This means that the variations in annual returns on these two stocks sometimes cancel each other so that overall portfolio risk initially falls as A is added to B. For details see Brealey and Myers (1991)

<sup>9</sup> The percentage mix of each stock is not given directly on the graph; each tick mark (circle), however, represents a 5% change in the portfolio mix.

Investors will choose a risk-return combination based on their own preferences and risk aversion. More risk-averse investors would be inclined to own relatively conservative portfolios such as V, while less risk-averse individuals will operate at S or A.



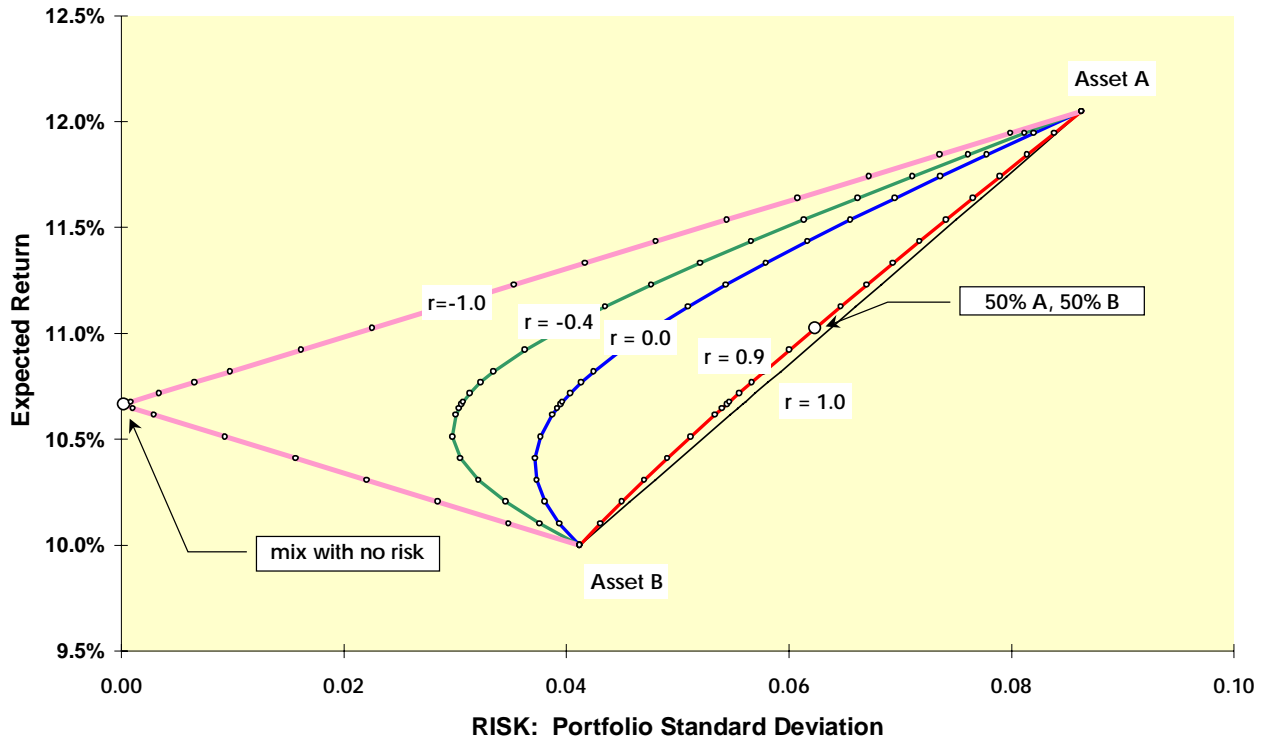
Source: S. Awerbuch, "Getting it Right: The Real Cost Impacts of a Renewables Portfolio Standard" *Public Utilities Fortnightly*, February 15, 2000

### Figure 1-1 Portfolio effect

A portfolio consisting of 100% A has a higher return but also higher risk or standard deviation than a 100% B portfolio. Taking a high correlation coefficient of  $r = 0.9^{10}$  implies that when B is added to a 100% A portfolio, returns and risks change in simple almost linear fashion. There is no particular advantage to a portfolio of 50% A and 50% B. While its risk is lower than a 100% A portfolio, its return is lower as well. Figure 1-2 illustrates this effect.

<sup>10</sup> The fuel prices of gas and coal in the US over the last 25 years exhibit this correlation coefficient -- details see later.

**Risk and Return for Two-Asset Portfolio  
Given Different Correlation Coefficients ( $r$ )**



**Figure 1-2 Risk and return for two-asset portfolio given different correlation coefficients**

However, if  $B$  and  $A$  returns are less strongly correlated, then the addition of  $B$  to an  $A$  portfolio will produce a significant *portfolio effect*. For example, for  $r = -0.4$ ,<sup>11</sup> the addition of  $B$  to a portfolio of  $A$  produces significant risk reduction relative to the return decreases. Finally, if returns of  $B$  and  $A$  move in perfect opposition (i.e.  $r = -1.0$ ) then it will be possible to construct a portfolio with no variance as illustrated.

**The Effects of a Risk-free Asset on Expected Portfolio Risk and Return**

Adding a riskless asset to the  $A$ - $B$  mix produces interesting and counterintuitive results. In financial portfolios riskless assets generally consist of US Treasury bills or other government bonds.<sup>12</sup> The term "riskless" is actually misleading since even short term T-bills *do* in fact, bear some risk: e.g.: their market value will fluctuate in response to changing interest rates.<sup>13</sup> For this reason T-bills are more

<sup>11</sup> This is the historic US coal-gas fuel price correlation coefficient for the years 1990-99, details see later.

<sup>12</sup> Fama and French (1998) show that US treasury obligations are an appropriate risk-free asset for European financial portfolios.

<sup>13</sup> Although investors are virtually certain to ultimately receive the face value at maturity.

properly called *zero-beta* assets,<sup>14</sup> to distinguish the fact that they are not truly free of risk, but are riskless when the returns are expressed in a particular manner.<sup>15</sup> This section describes the remarkable effect that so-called “riskless” Treasuries have on the financial portfolio. The discussion is extended in the next section to the case of multiple assets or generating technologies including wind alternatives that to some extent mimic the financial “risklessness” of T-bills.<sup>16</sup>

Figure 1-3 illustrates the effects of adding riskless US Treasury Bills— “T-bills”— that yield 5%, to the mix of risky assets A and B. The risk-reward curve for various combinations of A and B remains unchanged from Figure 1-1. The new element in Figure 1-3 is the straight line, which represents the risk-return combinations for portfolios consisting of risky and riskless assets.<sup>17</sup> Point M, the tangency point between the line and the curve, now becomes the optimal mix of risky assets (M consists of 60% A plus 40% B)<sup>18</sup> The solid portion of the straight-line gives the risk-return combinations for portfolios consisting of the mix *M* plus T-bills. For example, Portfolio *H* consists of 50% T-bills plus 50% of portfolio *M*.<sup>19</sup> As more T-bills are added, the risk/return point moves down the line until the portfolio consists of 100% T-bills and 0% *M*. At this point its risk and return are 0.0 and 5% respectively, as shown in Figure 1-3.

We can now more closely examine the powerful (and counterintuitive) impact that T-bills have on the portfolio. For example, portfolio H, which includes T-bills, has the same expected return as P, (which

<sup>14</sup> Beta is an index to measure systematic risk. Assets with betas greater than 1.0 tend to amplify the overall movements of the market. Assets with betas between 0 and 1.0 tend to move in the same direction as the market, but not as far. For details see Brealey and Myers (1991), p. 143.

<sup>15</sup> Treasury obligations are riskless only if: i) held to maturity *and* the return is expressed in *nominal* dollars, or, ii) the term is sufficiently short so that interest rates cannot change enough to make much difference [Herbst (1990), pp. 315-316]. When Treasury obligations are held to maturity the investor is assured of receiving the face value, although inflation may have eroded the original expected *real* return. The *zero-beta* idea reflects the fact that when held to maturity, the *nominal* returns have a zero variance and hence a zero covariance with the market portfolio.

<sup>16</sup> Based on a CAPM approach a number of renewables come as close as possible to representing a zero-beta asset. Portfolio theory however is based on total variability, which is the risk measure used throughout this analysis.

<sup>17</sup> The inclusion of the riskless asset, whose variance is zero, simplifies the mathematical formulation so that the risk-return combinations now fall on a straight line. This can be shown using the illustrative example of a 2-asset portfolio (equation 1.2). If asset *I* is risk free, then  $\sigma_1 = 0$  and  $\text{COV}_{12} = 0$  so that portfolio risk,  $\sigma_p$ , becomes  $\sigma_p = \sqrt{X_2^2 \sigma_2^2} = X_2 \sigma_2$  which is a straight line.

<sup>18</sup> The tangency point M is the portfolio mix that maximises the portfolio performance  $\theta$ ,  $\theta = \frac{E(r_p) - r_f}{\sigma_p}$

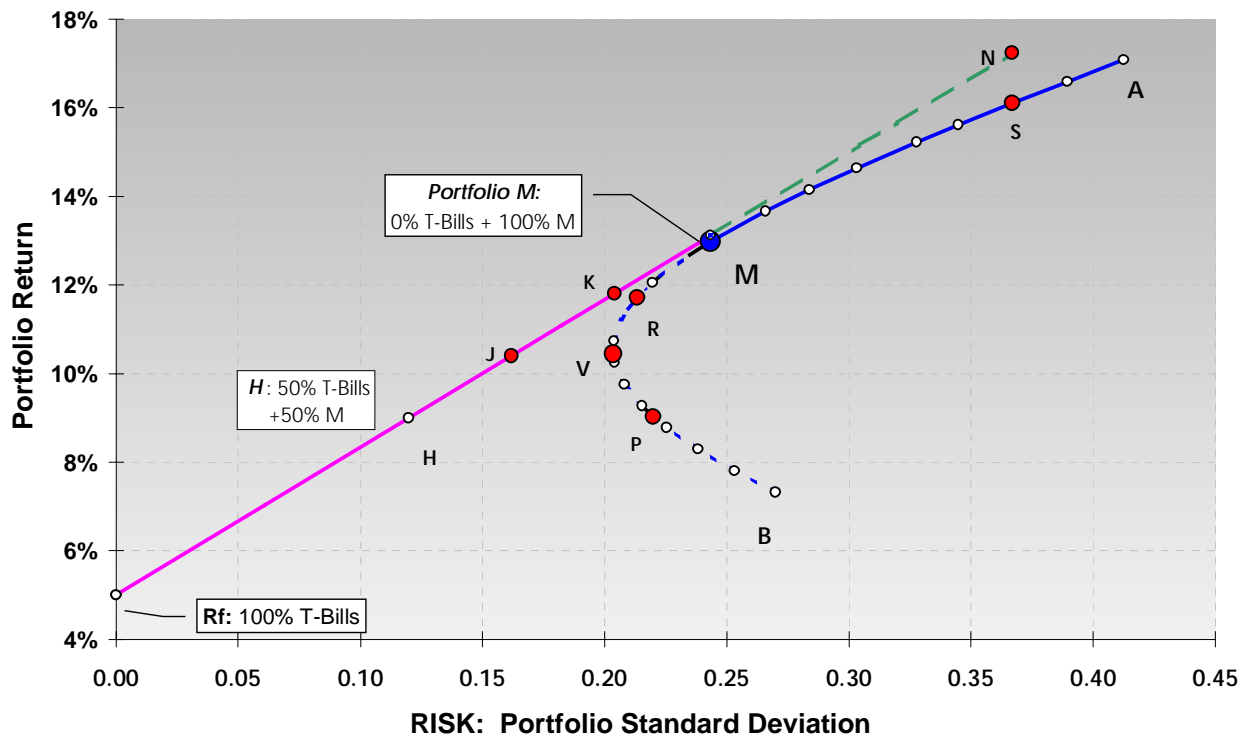
where  $E(r_p)$  is the expected portfolio return,  $r_f$  the expected return of the risk-free asset and  $\sigma_p$  portfolio risk – see Kwan (2001) p. 72.

<sup>19</sup> This means that Portfolio *H* consists of 50% T-bills, 30% A and 20% B.

does not) but is considerably less risky.<sup>20</sup> This illustrates that by including lower-yielding but riskless assets, we can create a portfolio that produces the same expected return, in this case 9%, but reduces risk. Similarly, T-bills, make it possible to move from portfolio V up to K, a move that raises return to 12% (from about 10.4%) without increasing risk. This again illustrates how riskless T-bills improve portfolio performance, raising expected returns without affecting risk.

With riskless assets, investors seeking risk-return combinations below M can construct portfolios such as K and J (which use a mix of M plus T-bills) that are superior to mixes such as V which consist of only risky assets. This powerful result holds in spite of the fact that T-bills generally yield less than risky stocks.

### Portfolio Risk and Return in the Presence of Riskless Assets



Source: S. Awerbuch, "Getting it Right: The Real Cost Impacts of a Renewables Portfolio Standard", *Public Utilities Fortnightly*, February 15, 2000

Figure 1-3 Efficient portfolios in the presence of riskless assets

<sup>20</sup> Note that P is below V and therefore not efficient.

### Multiple-Asset Portfolios: The efficient frontier

The portfolio selection method outlined above for two-asset portfolios can easily be extended to portfolios of three or more securities or assets.<sup>21</sup> Figure 1-4 is a standard representation of the risk/return possibilities of three or more risky assets. By mixing securities in different proportions, infinite risk-return combinations can be found as illustrated by the 'X' marks in Figure 1-4. Each X represents an individual portfolio.

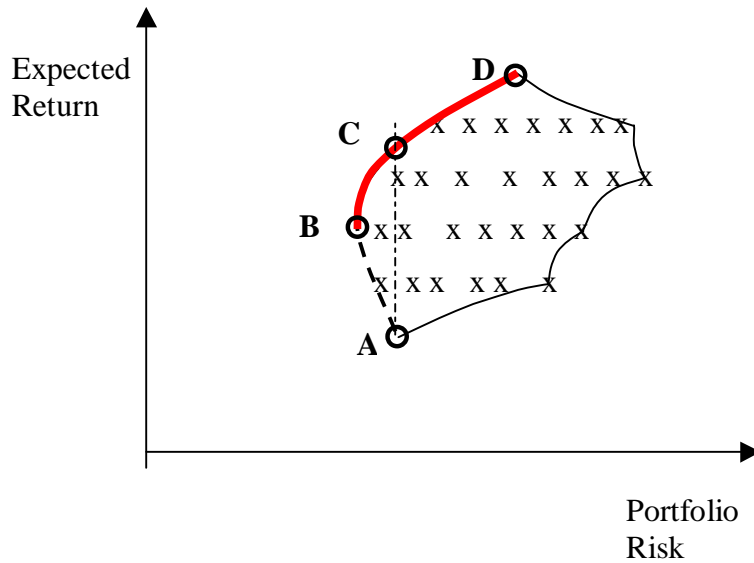
None of the interior portfolios are efficient since other mixes are available that yield the minimum risk attainable at a selected return level. The efficient portfolios all lie on a convex line called the *efficient frontier*, shown as the heavy solid curve BCD in Figure 1-4. The expected return of an efficient portfolio can be increased only by increasing its risk. This is not the case for inefficient portfolios, which lie to the right and below the efficient frontier.

Portfolios lying on the dashed part of the efficient frontier (between A and B) are also not efficient because other portfolios on the efficient frontier have the same risk but yield higher expected returns. For example, portfolio A is inferior to C since it exhibits the same level of risk but with lower expected returns (see the case of two assets).

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<sup>21</sup> The mathematical formulation is then extended following the scheme for two securities (see equation 1.2), i.e. each squared standard deviation is multiplied with its squared proportion in the mix. The respective covariation terms are added according to the pattern  $2 \cdot X_i \cdot X_j \cdot \text{COV}_{ij}$ . Therefore, for N securities equation 1.2 becomes

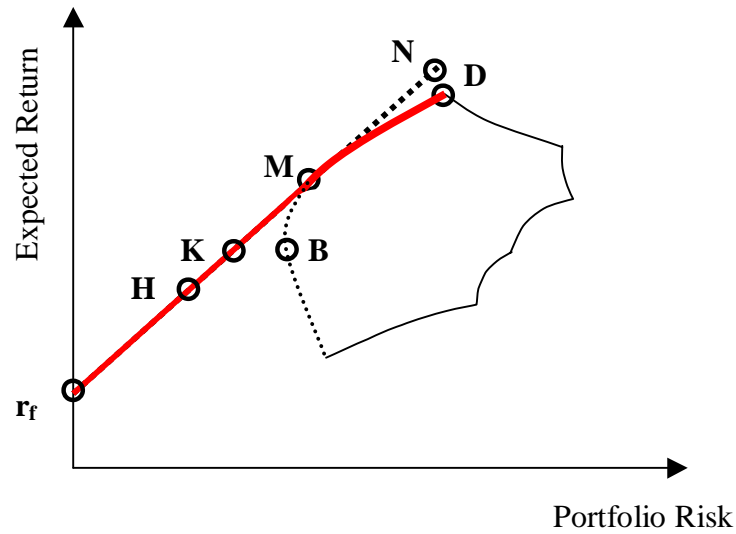
$$\sigma_p^2 = \sum_{i=1}^N \sum_{j=1}^N X_i \cdot X_j \cdot \rho_{ij} \cdot \sigma_i \cdot \sigma_j \quad \text{Equation 1.1 is extended to } E(r_p) = \sum_{i=1}^N X_i \cdot E(r_i)$$



**Figure 1-4 Efficient frontier of a portfolio with more than two risky securities**

### **Introducing a risk-free security to a portfolio of multiple risky assets**

Adding a riskless asset to a portfolio of risky assets (see above) produces important counterintuitive results. Figure 1-5 illustrates the effects of adding a “riskless” security, e.g. T-bills, to the mix of risky assets. The efficient frontier of Figure 1-4 has not changed its shape above the point M. The new element in Figure 1-5 is the straight line, which represents the risk-return combinations for portfolios consisting of risky and riskless assets. Point M, the tangency point between the straight line and the curve, now becomes the optimal mix of risky assets for all investors, independent of their risk-return preferences. The solid portion of the straight line gives the risk-return combinations for portfolios consisting of the mix M plus T-bills. For example, portfolio H consists of 50% T-bills plus 50% of portfolio M. As more T-bills are added, the risk/return mix moves down the line until the portfolio consists of 100% T-bills, point  $r_f$ , and 0% M.



**Figure 1-5 Portfolios with risky securities and a riskless asset**

This further illustrates that by including lower-yielding riskless assets, portfolios can be created that produce the same expected return at lower risk. With riskless assets, investors seeking risk-return combinations below M can construct portfolios such as K and H (which use a mix of M plus e.g. T-bills) that are superior to mixes that only include risky assets.

## 1.2 Application to generating portfolios

The relationships derived from financial portfolios may be applicable to portfolios of generating assets. In the case of generating or other *real* assets, market or historic cost risk can be defined in a manner that is analogous to the definition used for financial assets, i.e. market risk is measured on the basis of the historic variation and covariation of the *holding period returns* (HPRs)<sup>22</sup> of costs of the technologies considered [see e.g. Awerbuch (2000)].<sup>23</sup> These include conventional generating technologies (coal, oil, gas, nuclear) and fixed cost renewables, here wind. This transformation serves to create a set of portfolio graphs that resemble and can be interpreted much the same way as traditional textbook portfolio graphs. In essence, this makes it easier to interpret the correspondence between the analysis of real generation assets as compared to traditional financial portfolio analysis.

Analogous to the treatment of financial assets, whose expected return (i.e. annual return) measures an output or yield divided by an input or cost, generating costs are converted to return by inverting them.<sup>24</sup> The unit of expected portfolio return for generation assets becomes kWh/US cent.

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<sup>22</sup> See Footnote 6:  $r_t = \frac{EV_t - BV_t + CF_t}{BV_t}$  -- In the case of fuel prices  $CF_t$  is zero,  $EV_t$  is the fuel price per unit (kWh) at the end of period  $t$  and  $BV_t$  its price at the beginning of period  $t$ . If instead of the standard deviation of *holding period returns* the SD of fuel prices was used for risk appraisal the result would be distorted [Herbst (1990) p. 255]. A technology with high fuel prices might have a larger variance than one with lower fuel prices simply because of the magnitude of its fuel prices. Therefore, financial portfolio theory uses a relative measure to estimate the risk of assets, i.e. *holding period returns*.

<sup>23</sup> Since risk, properly defined, is a measure where “a probability density function may meaningfully be defined for a range of possible outcomes” [Stirling (1994)] the portfolio analysis limits us to those elements that are probabilistic in character. For details see Annex A.

<sup>24</sup> Expected returns are based on traditionally estimated levelised generation costs taken from WEO (2000). Our analysis is cost-based, since from a societal perspective, generating costs and risks are properly minimised. Our analysis is therefore not based on revenues from electricity sales, renewables’ feed-in tariffs or the price of conventional electricity. Since the analysis and the expected portfolio returns are cost-based, variations in electricity market prices are not relevant.

Financial returns generally reflect a benefit divided by an input, where both are dollar-dimensioned: i.e. “dollars-returned/dollars invested. The financial return measure is therefore dimensionless, a property that does not hold for our cost-based return measure: kWh/cent, which becomes dimensionless only if a monetary value is assigned to the numerator.

Multiplying our cost-based portfolio returns, [kWh/cent], by the price of electricity [cent/kWh] yields a dimensionless measure of return that is precisely analogous to the financial measure of return. This procedure however raises questions regarding the appropriate electricity price to use.

Electricity markets exhibit short-term price fluctuations driven by strategic behaviour of market participants as well as random daily events including generator outages, weather extremes, etc. Using instantaneous or even daily market prices would introduce additional risk to the portfolio. A relevant, dimensionless return measure for our purposes would be based on an averaged cost from WEO (2000) as representative of long-term equilibrium electricity market prices. However, for illustrative purposes it shall be stuck with the definition of returns as kWh/cent.

However, it is useful to note that portfolio theory is based on a set of assumptions which generally hold in highly efficient financial markets, but which may not be strictly analogous in the case of a portfolio of generating or other *real* assets. Some of these assumptions may not be crucial, while the importance of others still needs to be determined in the sense of how outcomes change when the assumptions are transferred. The standard assumptions require that there exist perfect markets for trading assets, which generally implies low transaction costs, perfect information about all assets and returns that are normally distributed.<sup>25</sup>

The market for the generating assets, e.g. turbines, coal plants, etc., may be relatively imperfect as compared to capital markets, which suggests that, unlike financial securities, which can be readily sold, investments in generating assets are less easily liquidated. In addition, financial securities are almost infinitely *divisible*, so that a portfolio can contain between 0% and 100% of a given security [Herbst (1990) p. 303]. Generating assets may be quite lumpy by comparison, which might cause discontinuities. For large service territories, however, or for the analysis of national generating portfolios, the lumpiness of individual capacity additions becomes relatively less significant.

Given these caveats, it is useful to note that portfolio theory is commonly applied to the valuation of tangible, non-financial assets, in spite of these limitations, see e.g. Springer and Laurikka (2002), Seitz (1990), Unger (1989), Helfat (1988) and Herbst (1990).

### **Stirling's "Ignorance and Diversity" versus Classical Mean-Variance Portfolio Theory**

Andrew C. Stirling (1994) rejected the applicability of mean-variance portfolio theory on the grounds that fuel price movements have no pattern. He argued that "Decisions in the complex and rapidly changing environment of electricity supply are unique, major and effectively irreversible."

Differentiating between 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..."

Stirling states that ignorance rather than risk or uncertainty dominates real electricity investment decisions. He conceptualizes *diversification* as a response to ignorance.

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<sup>25</sup> "By looking only at mean and variance, we are necessarily assuming that no other statistics are necessary to describe the distribution of end-of-period wealth. Unless investors have a special type of utility function (quadratic utility function), it is necessary to assume that returns have a normal distribution, [Copeland and Weston (1988) p. 153]."

Portfolio risk, however, is properly defined as total risk (the sum of random and systematic fluctuations) measured as the standard deviation of periodic historic returns. Portfolio risk, therefore, includes the random fluctuations of individual portfolio components, which have a wide variety of historic causes. Random risks would include an Enron bankruptcy, a particular technological failure, bad news about a new drug, resignation of a company's CEO, or the outbreak of unrest in oil-producing parts of the world. Total risk can be seen as the sum of the effects of all historic events, including countless historic surprises.

While no particular random event may ever be precisely duplicated, nonetheless, in the case of equity stocks, historic variability is widely considered to be a useful indicator of future volatility. Along these lines, it has been said that:

“By studying the past, one can make inferences about the future. While the actual events that occurred in 1926-1996 will not be repeated, the event-types (not specific events) of that period can be expected to recur [Ibbotson Associates (1998) p. 27].”

This study argues that this is no different for fossil prices, O&M outlays and investment period costs. In each of these cases, observed historic variability embodies a wide variety of random events. While these precise outcomes may never be perfectly repeated in the future, they at least provide a guide to the future.

This is not to say, however, that certain fundamental changes in the future, such as significant market restructuring or radically new technologies, could not create ‘surprises’ by altering observed historic risk patterns. Such radical, discontinuous change is generally unpredictable.<sup>26</sup> However, rather than letting such possibilities drive our decision approach, we find it more plausible to assume that the totality of random events, including wars and OPEC pricing decisions that have affected fossil prices over the last three decades, cover the reasonable range of expectations for the future.

#### Optimal Generating Portfolios for the US: Fossil Fuel Risk Only

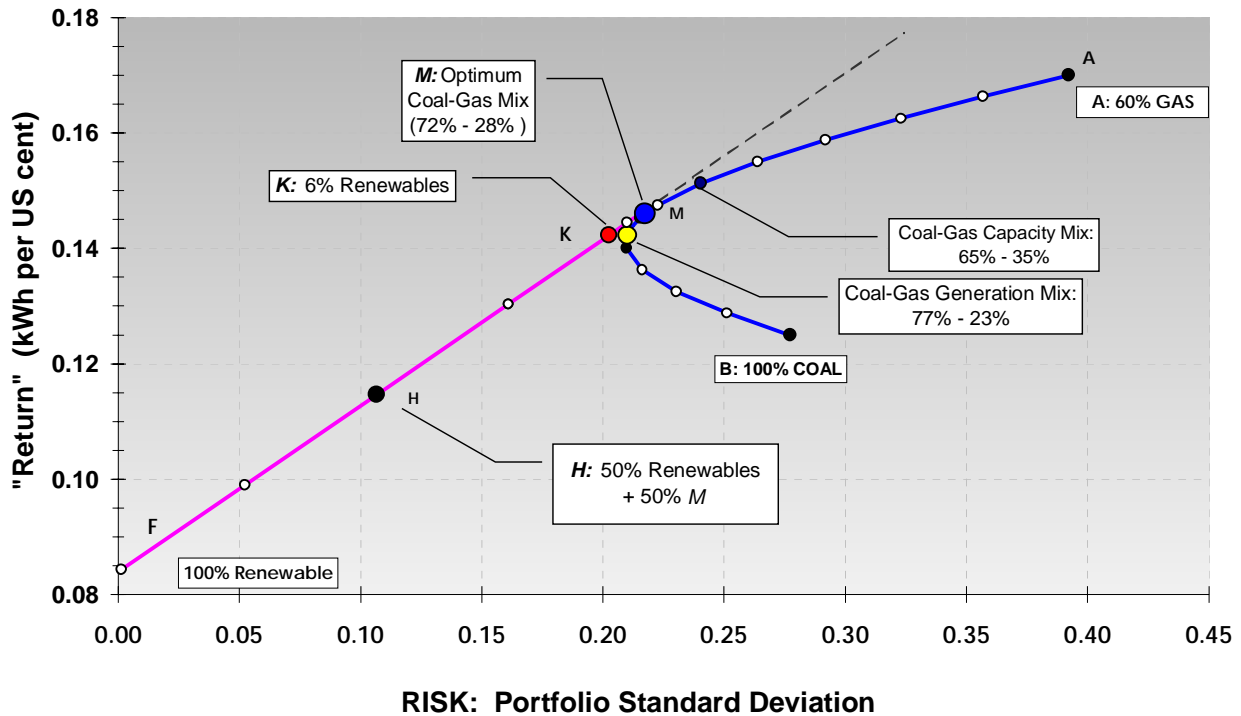
Figure 1-6 shows the illustrative result of a previous analysis of the US portfolio for electricity generation, [Awerbuch (2000)]. It uses historic data to develop return-risk results for a fossil portfolio consisting only of gas and coal.<sup>27</sup> The analysis is based on annual coal and gas fuel price data for the period 1975-99.

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<sup>26</sup> e.g. Strebel Paul, *Breakpoints: How Managers Exploit Radical Business Change*. Harvard Business School Press, 1992

<sup>27</sup> Costs are converted to returns by simply inverting them. The unit of portfolio return therefore is kWh/US cent.

**Risk and "Return" for Three-Technology US Generating Portfolio**  
**Assumed Cost for Riskless Renewable: \$.12/kWh**



Source: S. Awerbuch, "Getting it Right: The Real Cost Impacts of a Renewables Portfolio Standard", *Public Utilities Fortnightly*, February 15, 2000

**Figure 1-6 Portfolio theory applied to the US portfolio – renewables 0.12 \$/kWh**

The 100% coal portfolio (Point B) “yields” 0.125 kWh/US cent. Adding some gas to the mix at first reduces risk while simultaneously raising return.<sup>28</sup>

The minimum variance of the fossil portfolio (.21) occurs at a mix consisting of 77% coal and 23% gas.<sup>29</sup> After this point, further gas additions increase both risk and return until a 100% gas portfolio is obtained (Figure 1-6 is truncated at 60% gas – 40% coal for illustration purposes).

The straight-line segment represents portfolios consisting of the mix M combined with a riskless resource.<sup>30</sup> This is analogous to the previous case of financial portfolios. At F, (lower left) the portfolio

<sup>28</sup> This result is driven by the historic covariance of the fuel prices so that altering the levelised costs for A and B does not change this outcome.

<sup>29</sup> Each tick mark along the convex curve represents a 5% change in mix on the fossil portfolio.

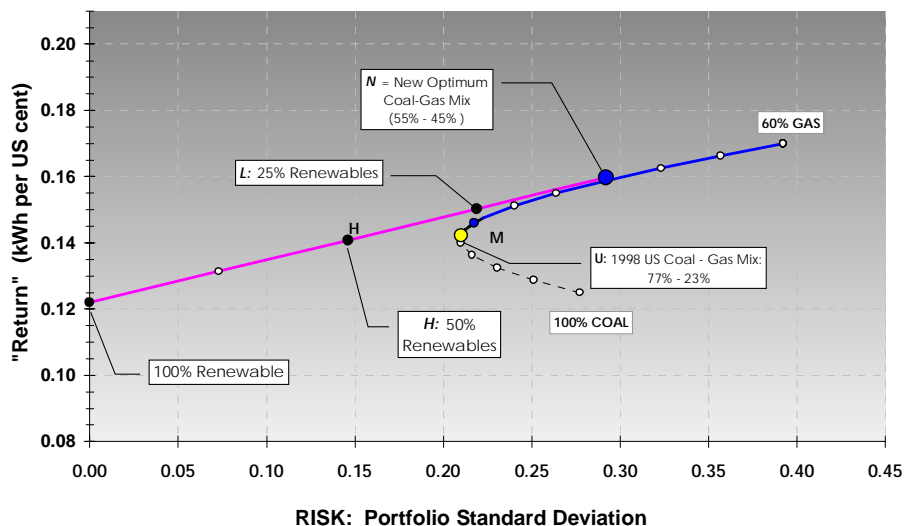
<sup>30</sup> This might be a passive renewable technology that does not exhibit fuel risk. For further details see the discussion in section 3.1.

consists of 100% passive riskless renewables.<sup>31</sup> Finally, at M, the portfolio consists entirely of the fossil mix.

The main results of this analysis are:

- The US policy of expanding the reliance on natural gas-fired generation will increase the risk of the US generating portfolio disproportionately to the modest cost reductions it attains.
- If generating cost of \$.12/kWh are assumed for the renewables bundle (which could consist of a mixture of, for example, wind, photovoltaics and small hydro), then it can be shown that adding between 3% and 6% renewables to the existing US gas-coal mix will serve to reduce cost and or risk.
- If cost for the renewables package can be reduced to \$.08/kWh, (still higher than gas and coal) then increasing the portfolio share of renewables to as much as 25% still leaves overall portfolio generating costs unchanged, but provides significant risk reductions, cf. Figure 1-7.

**Risk and "Return" for Three-Technology US Generating Portfolio  
Assumed Cost for Riskless Renewable: \$.08/kWh**



Source: S. Awerbuch, "Getting it Right: The Real Cost Impacts of a Renewables Portfolio Standard", *Public Utilities Fortnightly*, February 15, 2000

**Figure 1-7 Portfolio theory applied to the US portfolio – renewables 0.08 \$/kWh**

<sup>31</sup> Each tick mark along the line segment represents a 25% addition of the fossil mix M.

### 1.3 Risk/Return of the EU Generating Portfolio

We now extend the analysis to Europe, using the expanded model that incorporates the risk of O&M and construction period costs.<sup>32</sup> In addition, this model includes a procedure for calculating the efficient frontier—the location of all efficient portfolios. This enables the analysis to accommodate any reasonable number of additional technologies,<sup>33</sup> including oil and nuclear.

More importantly, the expanded model can accommodate a number of important additional technological distinctions. For example, it enables us to provide different cost and risk estimates for "existing" as compared to "new" technologies. Such distinctions are important in portfolio analysis for a number of reasons:

- First, as compared to existing assets, new generating technologies such as new generation gas turbines may have lower electricity generation costs in the form of improved efficiencies and lower O&M requirements. It is therefore vital to distinguish between the generating costs of the existing portfolio as compared to the potentially lower generating costs associated with new vintage portfolio additions.<sup>34</sup>
- Second, the risk of existing generating assets is tied largely to the future operating costs while new assets will in some cases also exhibit significant planning period risks.

Specifically, the expanded model reflects the market or cost risks for: i) fuel outlays, ii) variable O&M costs, iii) fixed O&M and iv) construction period costs. The generating costs used in this analysis are given in Table 1-1.<sup>35</sup>

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<sup>32</sup> The assumptions and limits affecting the analysis of generation portfolios are summarised in the Annex A.

<sup>33</sup> The current version of the Microsoft Excel™ spreadsheet model accommodates maximal nine technologies.

<sup>34</sup> The levelised investment costs of the existing generating assets do not reflect the percentage of assets that have already been depreciated in the existing EU mix.

<sup>35</sup> It is not differentiated between gas turbines and combined cycle gas turbines in this analysis.

**Table 1-1 Levelised annual costs of technologies used in the first two subsections (WEO 2000)**

LEVELIZED COST US cents / kWh	CCGT – Gas fired	Steam boiler – Coal fired	Oil <sup>36</sup>	Nuclear	Wind <sup>37</sup>
Fixed investment	0.64	1.24	0.59	2.26	3.08
Fuel	1.82	1.33	2.08	1.00	0.00
Variable O&M	0.13	0.28	0.15	0.03	0.00
Fixed O&M	0.18	0.28	0.15	0.66	0.89
<b>Total busbar cost</b>	<b>2.76</b>	<b>3.14</b>	<b>2.96</b>	<b>3.95</b>	<b>3.97</b>
<b>Return (kWh/US cents)</b>	<b>0.362</b>	<b>0.318</b>	<b>0.337</b>	<b>0.253</b>	<b>0.252</b>

### Cost Portfolios

The four cost categories associated with each technology can in themselves be viewed as a portfolio of four assets. Their standard deviations and correlation with the other cost types of this technology as well as their respective weightings, as a percentage of total levelised generation costs of a technology, are used for risk appraisal.

Based on Table 1-1 the weightings of, e.g., gas are, 23% capital investments, 66% fuel costs, 5% variable O&M and 6% fixed O&M. In the case of steam coal the percentages shift a little bit in favor of capital investments: 39.5% investment costs, 42.5% fuel costs, 9% variable O&M and 9% fixed O&M.

The risk for this sub-portfolio is calculated using the portfolio procedures from the preceding sections. The HPRs of costs of one technology will co-vary with the costs of the other technologies in the portfolios. Therefore, computationally, a two-technology-portfolio becomes an eight-technology-portfolio when the risk of all four cost categories is included.

In analogy with financial portfolio theory, riskless or tangible assets exist, e.g. investments in demand-side efficiency improvements. These assets are generally characterised by relatively high (riskless) capital and no fuel or O&M costs.

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<sup>36</sup> Based on authors' calculations;

<sup>37</sup> In general, the closer wind gets to its maximal 2010 technical potential [Huber et al. 2001] the higher its generation cost will be since the least profitable plants will be the ones lastly constructed. I.e. the windiest sites will probably be the first ones to be exploited such that the least windy site is left till the end. However, this interrelation between capacity installed and generation costs for RES will not be considered in this work.

Passive renewable technologies, such as PV or wind, have no fuel costs and therefore do not bear fuel risk.<sup>38</sup> Moreover, due to their high modularity, availability and short lead-times their construction period risk can be ignored as well [e.g. Brower et al. (1997), Hoff (1997) and Venetsanos et al. (2002)].

### Calculating the Efficient Frontier

Lagrange multipliers are often used in the analytic formulations of efficient frontiers<sup>39</sup> although optimisation procedures are also available and practical. For example, the expanded portfolio model finds the optimal or efficient portfolio set using Microsoft Excel<sup>TM</sup> SOLVER, which employs an iterative procedure to plot the minimum risk portfolio combination for each level of return.<sup>40</sup>

### Portfolios consisting of conventional technologies— coal, gas CCGT, nuclear and oil— and wind.<sup>41</sup>

Risk is initially based solely on fuel price risk, computed on the basis of annual data for the period 1994 – 2000.<sup>42</sup> The analysis is then taken further by also including O&M risk, and the analysis is completed by including investment and planning period risks. The inclusion of investment period risks

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<sup>38</sup> We are aware of the fact that fluctuations in renewable electricity generation due to e.g. variable wind availability cause additional *opportunity costs*. These opportunity costs bear risk since often risky sources, i.e. fossil fuels, serve as backup. In this analysis we assume that there is no backup capacity necessary in addition to the existing. We do not take into account any opportunity costs - and hence risk - for wind electricity generation. Considering the EU electricity grid to be ONE grid and given that the year 2010 mid-term potential is approx. 7.9% of the EU-2010 el. generation [Huber et al. 2001] this assumption is underpinned by studies claiming that wind penetration levels of 5% to 10% cause little or no change in the current operation strategy [Wind Energy Weekly (1996), ERU (1995)].

<sup>39</sup> For the principal methodology see e.g. Copeland and Weston (1988) p. 119 or Sharpe (1970) pp. 239-243

<sup>40</sup> For details see Kwan (2001).

<sup>41</sup> The EU “renewables directive” 2001/77/EC sets a target of 22% RES-E for the Community in 2010. RES-E are defined as wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases. The analysis presented in this paper only means to expose schematic results and will therefore deal only with wind in a first step. Subsequently other renewables indicated in the “renewables directive” will be considered. This might be done via a “bundle” of fixed cost, modular renewable, such as a mixture of wind, PV, hydro and a second bundle of other renewables, as biomass, geothermal, etc.

<sup>42</sup> The time period was chosen to better show the *portfolio effect* with three technology mixes. For all successive analyses the time period 1989-2000 is used because we assume that the latter is a less biased guide to the future.

necessarily makes sense only where existing capacity is differentiated from new capacity.<sup>43</sup> The results of the final analysis are therefore considerably more complete in certain respects and have more meaningful interpretations for policy making.

### **Efficient portfolios reflecting fossil fuel price risk only**

For expository purposes to examine three conventional technologies, we begin the discussion with a simplified case that reflects only fossil fuel price risk for three conventional technologies.<sup>44</sup> Though simplified, it turns out that this case does not bias outcomes significantly since fuel costs constitute the major part of total generation costs for these three technologies (Table 1-1).<sup>45</sup>

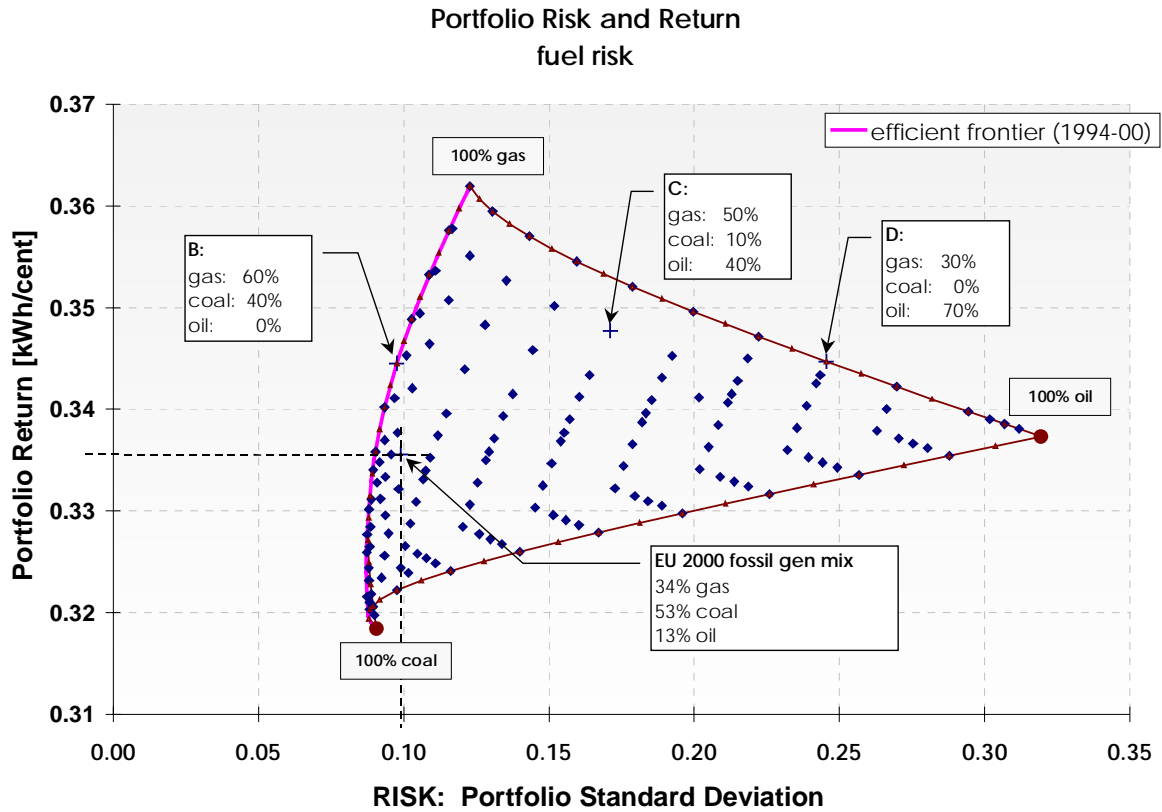
Figure 1-8 shows the risk and return for portfolios consisting of various combinations of the three technologies, coal, gas and oil.

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<sup>43</sup> Investment and planning costs of existing capacity are already sunk and do not expose investors to risk.

<sup>44</sup> For our analysis, it remains to be determined whether the fuel price HPRs are actually normally distributed. However, fossil fuel prices are commonly modelled as *random walks* [see e.g. Felder (1994), Hassett and Metcalf (1993), Holt (1988), Glynn and Manne (1988)], which implies that price changes are at least independent.

<sup>45</sup> For the sake of exposition, the weighting associated to fuel variation is 100% in this analysis. Taking the levelised generation costs of e.g. gas, 23% come from capital investments, 66% stem from fuel costs, 5% from variable O&M and 6% from fixed O&M (WEO 2000). Hence, in order to make the analysis of the following sections comparable to the actual one the weighting of gas fuel risk should be 66%.



**Figure 1-8 Portfolios of three conventional technologies applied to the EU – fuel risk**

The graph can be interpreted as follows: a portfolio consisting entirely of oil, has a return of 0.337 kWh/US cents (equivalent to a generating cost of 2.96 cents/kWh) and a standard deviation (SD) of 0.32. As coal is added to this portfolio, both risk and return drop, until the portfolio consists of 100% coal, with a risk-return of 0.09 and 0.318 kWh/US cent. Each tick mark along the oil-coal line, which shows the risk-return for all possible oil-coal combinations, represents a 5% change in mix.

The oil-gas and the coal-gas lines have similar interpretations.<sup>46</sup> These three lines define the feasible two-technology-combinations. Observe that when gas is added to the 100% coal portfolio, risk initially falls— though only slightly— as the return rises. Unlike the recent US results, costs for these three technologies in Europe are quite highly correlated so that there is little “portfolio effect”, as compared to the US case.

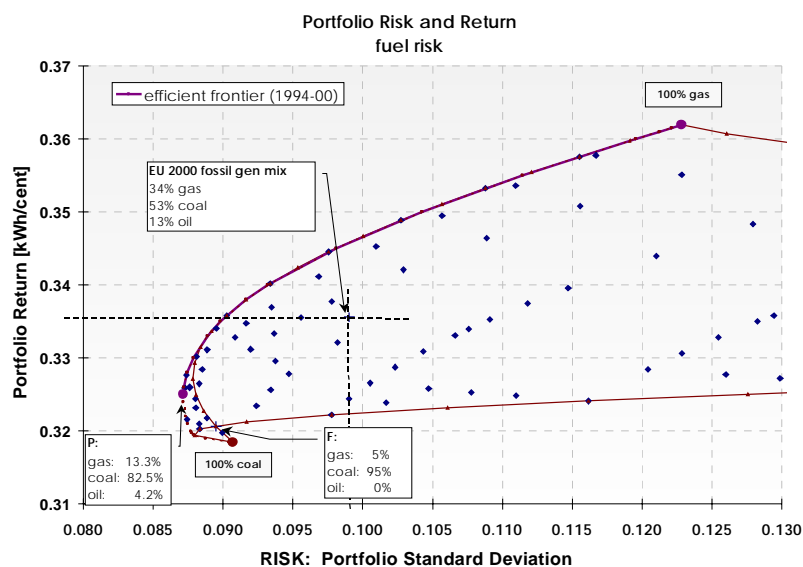
Point B is one possible coal-gas combination representing 60% gas, 40% coal and 0% oil. The dots on the interior of the feasible region, such as the one at point C, represent just some of the infinite

<sup>46</sup> Note that the coal-gas line is equivalent to the portfolio curve in Figure 1-6 for the two-technology US portfolio

possible combinations of the three technologies. Whereas only two-technology portfolios, such as mixes B and D, are located on the perimeter (not on the efficient frontier) the interior dots all represent three-technology-combinations.

Figure 1-9 shows the coal-gas line in greater detail so that the efficient frontier becomes more clearly visible. This enlargement shows an interesting result: the lower section of the efficient frontier lies to the left of the coal-gas line. Points on this frontier, to the left of the coal-gas line, are of particular interest because they illustrate a somewhat counterintuitive outcome: by introducing oil — the riskiest alternative— into the coal-gas mix, risk is actually reduced. For example, point P in Figure 1--9 has lower risk and equal return than a portfolio on the coal-gas line which contains no oil.

This outcome is surprising, as described, because on a stand-alone basis, oil is considerably more risky than coal or gas. In the portfolio mix, however, the outcome makes sense: it is an illustration of the portfolio effect which occurs when the returns of two (or more) assets are less than perfectly correlated (i.e.  $\rho < 1.0$ ), although it is not significant where correlations are high, say on the order of +0.7 or greater. The correlation coefficient for the HPR of coal and oil is quite low with 0.02. By contrast gas and oil as well as gas and coal have correlation coefficients of approximately 0.5. This explains why the introduction of oil into the coal-gas portfolio reduces risk. As the share of coal rises, the efficient frontier diverges more from the gas-coal line. Since the correlation coefficient between coal and oil is close to zero the more coal is included in the three-technology portfolio the more this effect becomes visible.



**Figure 1-9 Enlargement of the figure showing the portfolios of three conventional technologies applied to the EU – fuel risk**

### Four conventional technologies

Next, we introduce nuclear generation, the technology that dominates the actual EU electricity mix, into the portfolio.<sup>47</sup> The cost characteristics of this technology differ from fossil technologies in that capital and O&M costs are considerably higher relative to fuel costs. For nuclear generation, therefore, fuel risk does not encompass most of the technology's risk.<sup>48</sup> In addition, nuclear fuel price risk is not sufficiently captured by uranium fuel prices alone, since the ore undergoes enrichment, conversion, and fabrication steps before it can be used to generate electricity. Historical time series show that these additional processes are also subject to significant price variability.

Finally, there is no universally defined and accepted marketplace for uranium, its enrichment and conversion. The market for uranium fuel fabrication is even less open and often exhibits strong technical ties between suppliers and plant operators. Also, in many countries, a large part of nuclear fuel cost is essentially indigenous and therefore subject to different risks from those purchases made in the international marketplace.<sup>49</sup>

Historic time series data for natural uranium, conversion and enrichment costs were summed, taking account of their relative individual weightings.<sup>50</sup> Next, periodic HPRs were computed.<sup>51</sup> Since uranium fuel fabrication seems to add little variability to the fuel cost stream (see above) and as there was no historical time series available it was omitted for risk appraisal.

As stated before passive renewable technologies with zero fuel costs, such as PV, wind, hydropower, geothermal, landfill gas etc. do not exhibit fuel risk. Hence these technologies might be considered as

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<sup>47</sup> EU generation data reported for 2000 (preliminary): nuclear 33.8%, coal 27.1%, natural gas 17.2%, hydro 12.3%, oil 6.6%, combustible renewables & waste 1.9%, solar & tide & wind 0.9%, geothermal 0.2% (Electricity Information 2001). If only the conventional technologies are considered their respective shares are 39.9% nuclear, 32.0% coal, 20.3% natural gas and 7.8% oil. Together they make up about 85% of the EU electricity generation mix.

<sup>48</sup> This analysis deals only with risk stemming from variances and covariances of HPRs. Other sources of risk, such as risk of a Maximal Credible Accident decommissioning costs or spent fuel storage are not considered (see Annex A).

<sup>49</sup> Personal communication Mr Peter Wilmer, Nuclear Energy Agency, 2002.

<sup>50</sup> The variations add up according to equation 1.2.

<sup>51</sup> Historical spot market data for natural uranium were taken from EURATOM (ESA 2000). As for "conversion" it was referred to monthly data from "Nuclear Review" (March 2000). Concerning "enrichment services" a time series was extracted from "Nukem Market Report 2000" (May-June 2000).

riskless assets in this part of the analysis in the sense that their year-to-year costs are virtually unchanged, [e.g. Awerbuch (1993) and (1995a)].<sup>52</sup>

As previously discussed, the risk-free technology in the analysis can be conceived as a bundle of fixed cost technologies such as wind, PV, or hydro with an average cost of \$.04 USD/kWh. We continue to represent this “bundle“ with wind because this resource in particular is widely accepted and rapidly growing. Moreover, it is consistent with the conceptual risk-free renewable asset as discussed before: it is a modular energy source that has very short construction lead-time and hence presents essentially no construction period risk.

The results are shown in Figure 1-10.<sup>53</sup> As before, the light-weight lines show the location of the two-technology-portfolios. The efficient frontier of the risky generation assets is the solid convex (pink, if seeing in color) line extending from the 100% gas portfolio down to the portfolio located at the point P. Observe that this curve actually extends down from P to the 100% nuclear point, although this portion, shown as a dashed line, is not efficient because for a given risk level, higher returns are obtainable above the point P. As before, the point M is the optimal mix of the risky conventional technologies and therefore contains no wind. The mix at point M consists of 41% gas, 42% coal, 17% nuclear and 0% oil. Portfolios such as R, represent combinations that include the conventional mix represented by M, as well as wind. The analysis of this section uses the following cross correlation estimates, Table 1-2.

**Table 1-2 Empirically estimated cross correlations of HPRs of fuel cost streams**

	GAS	STEAM COAL	CRUDE OIL	URANIUM
GAS	-	0.48	0.46	-0.27
STEAM COAL	0.48	-	0.24	-0.13
CRUDE OIL	0.46	0.24	-	-0.37
URANIUM	-0.27	-0.13	-0.37	-

<sup>52</sup> While the costs are virtually riskless this does not imply that they are entirely free of risk. For example, weather can affect annual revenues (although year-to-year variations in insolation are quite small), but this risk is random– i.e.: it is not correlated to other costs such as fossil fuel prices, which means that it can be diversified away. This might be done by owning geographically dispersed sites or, perhaps, by using two or more different technologies, e.g. PV and wind. Finally, weather and other hedges can be purchased although these are not costless and may not be riskless. For further details see Awerbuch (2000), and Pethick and al. (2002)

<sup>53</sup> The remaining analysis is based on historic data for the period 1989-2000. As stated before we scaled the portfolio risk in this section to be different from the following ones, relatively overstating fuel risk. See also footnote 45.

Figure 1-10 provides useful insights to the risk-return of current and projected EU conventional generation mix (EU-2000, EU-2010).<sup>54</sup> Observe that the EU-2000 CON mix is very close to the efficient frontier. When viewed only from the perspective of fossil fuel price risk, therefore, the existing EU *conventional* mix is an almost-efficient combination of the generation types. However, this situation changes dramatically when we permit the inclusion of a risk free technology such as wind, which enables portfolio risk to be reduced. For example, portfolio *R*, which consists of a mix of 30% wind and 70% of point *M*'s portfolio, exhibits the same return as the EU-2000 CON mix but is less risky.<sup>55</sup>

The analysis of this section, which reflects fossil price risk only, therefore encourages a shift from the EU-2000 CON to, for instance, points such as *R*, which have the same expected return (i.e. overall generating cost) but at a lower risk. Transitions to points such as *R*, are made by introducing wind into the EU-2000 CON mix—as much as 30% according to the figure, based solely on the portfolio risk-return developed using the standard mean - variance approach.<sup>56</sup>

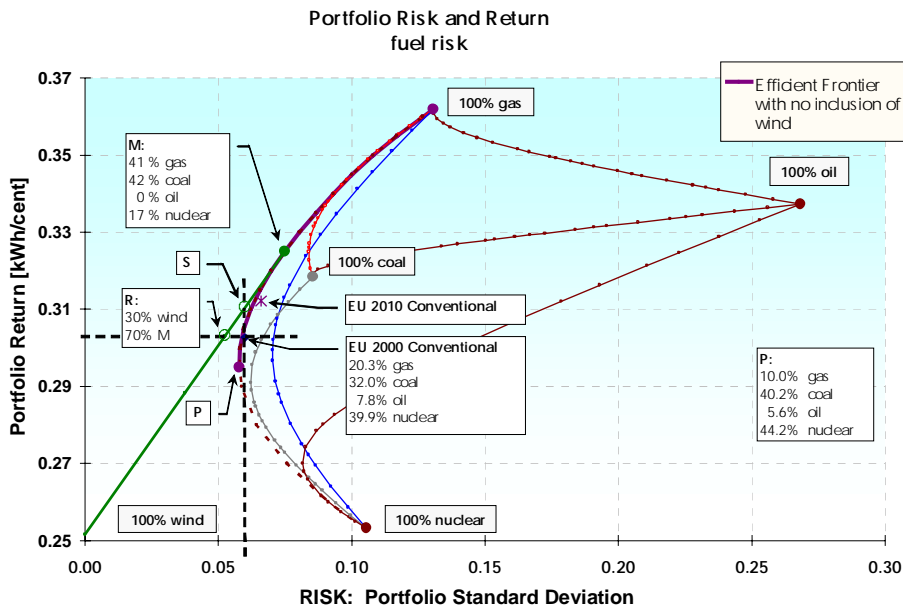
In addition to the Portfolio *R*, other efficient solutions are possible. For example, the existing EU-CON mix could be shifted over time to mixes reflected by points such as *S*, which exhibit the same risk as the EU-2000 mix but reduce generating cost (increase expected return). Therefore, by moving along the efficient frontier (EF) - now the straight segment or riskless asset line until *M* and then the EF of risky assets until 100% gas – policy makers can make a range of efficient risk-cost tradeoffs. Some of these tradeoffs, however, may be influenced or limited by political or technical considerations not reflected in this analysis. This is discussed next.

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<sup>54</sup> In this part of the analysis only four risky technologies are considered. Note that while EU-2000 corresponds to 2,167 TWh, EU-2010 equals 2,449 TWh. This is approximately 85% of the total actual generation and 82% of the projected mix for 2010.

<sup>55</sup> For a different risk free technology point *R* could shift to the left or to the right.

<sup>56</sup> This does not reflect any potential network constraints or other issues such as intermittency and technical potentials, which might not be important at this level with a 'bundle' of renewables.



**Figure 1-10 Portfolios of four conventional technologies applied to the EU – fuel risk**

### Optimality and practical feasibility of the 2010 portfolios

The last section illustrated the point that when fuel price is the only risk, the range of efficient or optimal generating portfolio choices will include some proportion of riskless or fixed cost technologies such as wind. However, practical and other constraints may alter the efficient solutions presented. For example, the feasible solution may contain more nuclear because plants cannot or will not be decommissioned in the near future. This section explores solutions that may be practically more feasible than those of the last section, and evaluates the extent to which these solution affect risk and return. Figure 1-11 shows the projected EU 2010 CON mix.<sup>57</sup> This 2010 mix can reasonably be assumed to correspond to the outcome of current policies projected to 2010.

Compared to the EU-2000 CON, the EU 2010 CON mix is riskier and offers higher returns (lower costs).<sup>58</sup> No economic gain is produced for society by moving from the EU-2000 CON to her projected 2010 mix: the move reduces generating costs, but increases risk. This means that some members of society will be pleased, while other, more risk-averse members will be less happy. Overall, the move produces no efficiencies or welfare gains.

Further, as compared to *M*, the *optimal* conventional mix, the EU-2010-CON-mix contains more oil and more nuclear, but less gas and coal. Its risk and return are both lower than *M*. Unlike *M*, the EU-

<sup>57</sup> Prepared by Electricity Information (2001)

<sup>58</sup> Note that they correspond to different amounts of electricity generated.

2010 CON-mix is less than efficient in the sense that both its risk *and* return can be improved by adding fixed-asset resources to the mix. For example, by introducing wind, the risk-return of the EU-2010 CON will shift to points such as  $R'$ , which represent improvements that produce societal welfare gains. These gains are created because the same electricity is produced at lower risk (points  $R'$ ). In short, the politically feasible solutions represented by EU-2010-CON are inferior to the ones composed of  $M$  and a risk-free technology.

Finally, we examine a scenario consisting of a portfolio with no oil since its actual share in the EU generation mix is already quite low and a phase out might be desirable, cf. “EU-2010 no oil” in the figure. This mix exhibits lower risk and return than both EU-2010 CON and EU-2000 CON. The inclusion of wind, which results in a mix of wind & “EU-2010 no oil”, would lead to significantly lower risk / return than with EU-2010 CON.

The previous sections have discussed the efficiency of various generating portfolios and shown the possible tradeoffs policy makers might choose along the efficient frontier. However, the previous graphs have not explicitly shown the changing technology mix along the efficient conventional frontier. This is given in Figure 1-12, which shows how the mix of conventional fuels changes along the efficient frontier. The results more clearly display the technology shifts needed to move along the frontier. For example, high risk/high return portfolios are dominated by gas generation. As risk and returns fall, (i.e. as costs rise), the share of gas declines while the share of coal and nuclear rises. An infinite number of portfolio mixes can be constructed to yield an overall return of 0.295 kWh/cent – costs of 3.4 cents/kWh. However, as shown in Figure 1-10, the **optimal** or minimum risk (conventional) portfolio at this return level,  $P$ , contains about 10% gas, 40% coal, 6% oil and 44% nuclear.

Stated differently, 1-11 depicts the shape of the efficient frontier– i.e. the cost of trading off return against risk, while Figure 1-12 shows the conventional technology changes required to make these risk/return trade-offs.

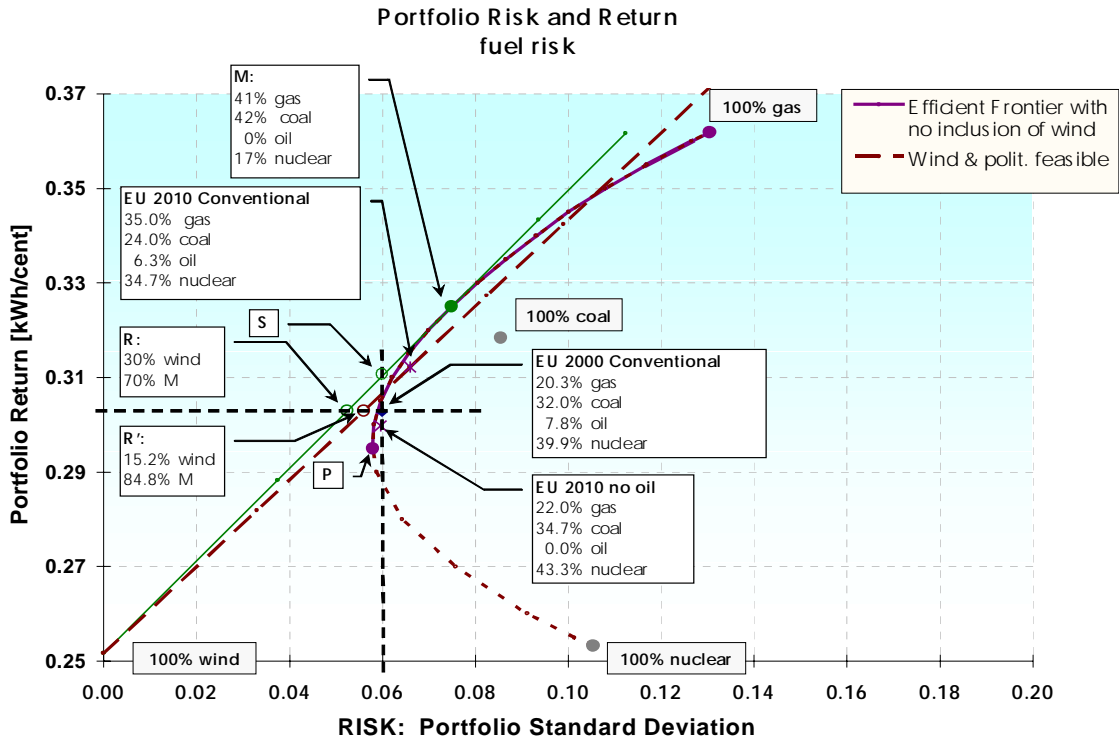


Figure 1-11 Practically feasible solutions

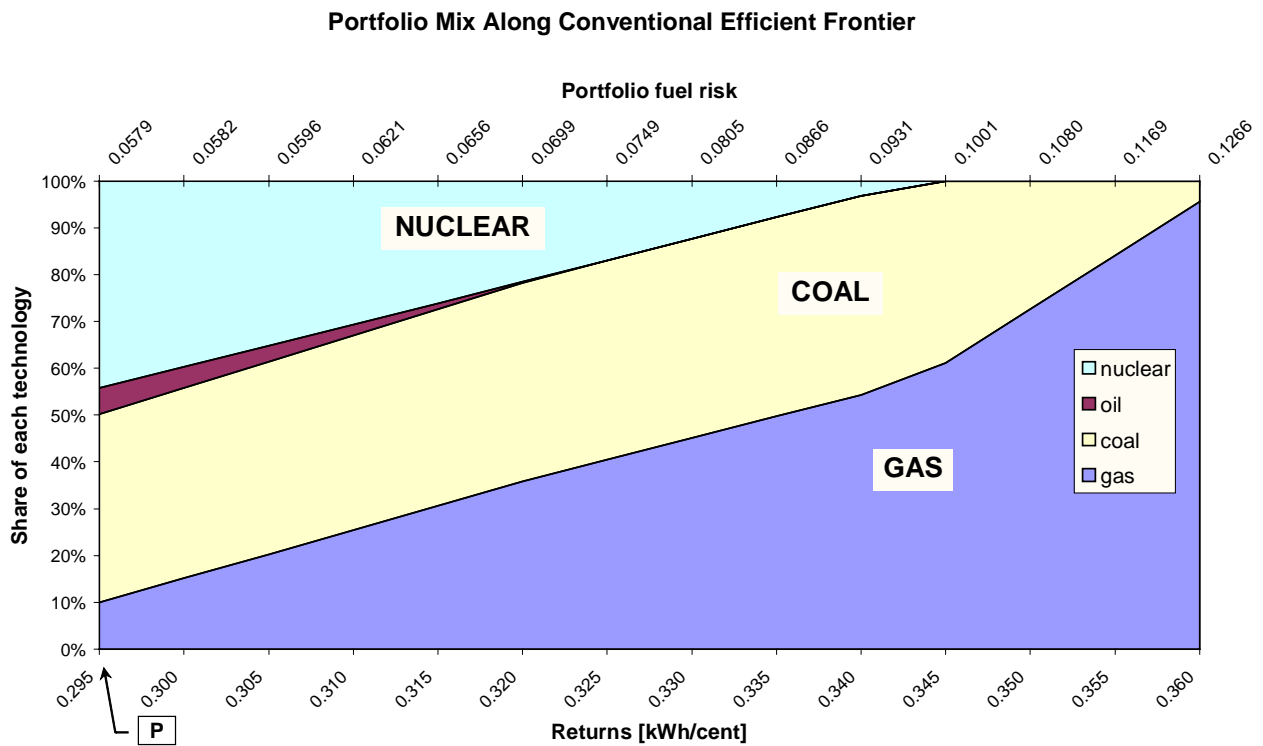


Figure 1-12 Portfolio mix along the efficient conventional frontier - fuel risk

This section has introduced the portfolio concepts and shown how the analysis can provide important guidance to policy makers. The next section explores the portfolio analysis using a more realistic case that reflects the variability of O&M costs.

### **Adding operation and maintenance cost risk**

The previous section introduced the portfolio analysis methods using models that reflected only fuel price risk. Though simplified, these models are most likely unbiased to the extent that fossil price risks dominate other portfolio risks. The simplified models produce useful insights regarding the optimality of existing and projected generating portfolios for the European Union. The primary conclusions of the simplified model is that the addition of wind and other fixed-cost technologies to the EU-2000-conventional mix and the EU-2010-CON-mix serves to produce welfare or efficiency gains in the form of risk and cost reduction.

This section extends the analysis, by adding the risks associated with O&M outlays. The addition of O&M risk captures all market risk associated with existing plants since their investment costs are already sunk and hence represent no risk.<sup>59</sup> The addition of construction period risks for new capacity, discussed in later sections, involves discriminating between new and existing generation capacity, which also enables us to distinguish between the costs and efficiencies of each. The final set of optimal portfolios presented in Section 3.4 therefore reflects efficiency gains and cost reduction for new capacity additions as well as the additional construction period risks they will encounter. We note however, that the general message of the simplified fuel-risk-only model discussed in the previous section does not materially change as its complexity and sophistication is increased.

Capital intensive, renewable technologies, such as wind, PV, hydro, geothermal, solar thermal, etc. are risk free when only fuel risk is considered as discussed in the last section. When O&M risk is added, these technologies in fact bear some degree of market or cost risk. The O&M costs of renewable technologies, will vary in systematic manner and will also exhibit some degree of systematic covariance with the O&M costs of other technologies. This eliminates the straight-line portion of the efficient frontier shown in the last section.

### **A proxy method for estimating O&M risk**

In the case of financial assets, estimates of historic variability are performed using historic HPR data. In the case of O&M costs, given sufficient historic cost data, the variances and co-variances could likewise be estimated in the usual manner. However, we did not have access to such data and therefore estimated O&M cost risk using financial proxies. In other words, we assumed that fixed and

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<sup>59</sup> Salvage and decommissioning costs are not considered and will be included in subsequent studies (see Annex A).

variable O&M costs have a risk pattern similar to the known variability of certain financial instruments. For example, we assumed that fixed O&M costs present a "debt equivalent" risk [e.g. see Brealey and Myers (1991) p. 473-474]. Fixed O&M costs are contractual in nature— as long as the owner of a generating station has sufficient income, the fixed O&M will be performed. This is a risk that is very similar to the risk of the firm's interest payments, which also will continue as long as there is sufficient income.<sup>60</sup> As a proxy for fixed O&M risk we therefore use estimates of the historic standard deviation for various corporate bonds as provided by Ibbotson Associates (1998) and as shown in Table 1-3.

We use a similar financial proxy method for estimating the historic risk or variance of variable O&M costs. In accounting terms, variable O&M costs are, by definition, conceptualised as volume-driven, i.e. they vary with kWh output. In addition to fluctuating with electricity output, which no doubt is related to economic cycles, variable O&M outlays will also fluctuate with the costs of labour and material, which also have a systematic covariance with economic activity. We assume the variable O&M cost risk to be equivalent to the overall market risk or variability of a broadly diversified market portfolio such as the S&P 500 (or the Morgan Stanley MCSI Europe Index). This variability is significantly higher than the historic SD of corporate bonds (Table 1-3).

The above estimates for fixed and variable O&M are somewhat arbitrary and ideally and should be refined and tested using actual historic field O&M cost experience. We subsequently use a series of sensitivity analyses to further evaluate these estimates, (see Annex B). The financial proxy data used to estimate O&M variability is given in Table 1-3, which shows the historic standard deviation of returns for various financial assets. The standard deviation (SD) of a broadly diversified market portfolio is approximately 20% (percentage points) while the SD for government and corporate bonds range from 3.2% to a high of 9.2% depending on the source and time period.

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<sup>60</sup> To be precise, interest payments are somewhat less risky than O&M outlays since available income will be used to first cover these payments.

**Table 1-3 Standard deviations of total returns for different assets<sup>61</sup>**

<b>Time Period</b>	<b>mean<sup>62</sup> [%]</b>	<b>Annual SD [%]</b>	<b>Type of Security</b>	<b>Source</b>
1926-1997	17.7	33.9	Small company stocks	Ibbotson Associates (1998), p. 122 Table 6-7
1926-1997	13.0	20.3	Large company stocks	Ibbotson Associates (1998), p. 122 Table 6-7
1928-2001	12.1	20.1	Stocks (S&P 500) <sup>63</sup>	New York University, Leonard N. Stern School of Business <sup>64</sup>
1926-1997	5.6	9.2	Long-term Government bonds	Ibbotson Associates (1998), p. 122 Table 6-7
1926-1997	6.1	8.7	Long term Corporate bonds	Ibbotson Associates (1998), p. 122 Table 6-7
1926-1998	3.8	3.2	Treasury bills	Ibbotson Associates (1998), p. 122 Table 6-7

Historic labour costs provide a second means for estimating the SD of O&M. Such estimates should be reasonable to the extent that systematic fluctuations in fixed and variable O&M costs are caused by labour cost changes. Table 1-4 shows the estimated standard deviations for a set of historic labour cost data for various countries. The three data sources must be compared with caution since the analysed time periods, the sectors and the statistical methods and definitions used are different for each. This being said, the calculated standard deviations are in the range of 1.6% and 10.7%.

For the analysis presented in this report, we use the financial proxy estimates and, as previously mentioned, coupled with sensitivity analyses, (see Annex B), which suggest our results are sufficiently consistent. We therefore leave the estimation of more reliable O&M standard deviations to future work. The following analysis is based on a standard deviation of 8.7% for the fixed O&M and 20% for the variable O&M.

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<sup>61</sup> Not inflation adjusted, percentages (%) are “percentage points”

<sup>62</sup> Arithmetic mean

<sup>63</sup> Weighted index of 500 stocks often used as an estimation of the performance of the whole market.

<sup>64</sup> <http://www.stern.nyu.edu/%7Eadamodar/pc/datasets/histretSP.xls>, last accessed 17 Jun. 02

**Table 1-4 Standard deviations of HPR of labour costs**

Source: ILO (2001)<sup>65</sup>, EUROSTAT New Cronos Database<sup>66</sup>, Bureau of Labour Cost (BLC) - Statistics Data (2002)<sup>67</sup>

Time period	Country	Specifications	SD of annual HPRs [%]
1987-1996	USA	labour costs	2.1
1985-1997	Germany	labour costs	1.6
1985-1997	Austria	labour costs	9.7
1995-2001	EU	wages & salaries <sup>68</sup>	10.7
1995-2001		total labour costs	8.1
1985-2001	USA	wages & salaries <sup>69</sup>	0.6
1986-2001		total labour costs <sup>70</sup>	0.7

### Co-variance of O&M Costs with other Cost Streams

In addition to specifying the standard deviations for each cost stream the portfolio model also requires that correlation coefficients (equation 1.2) be specified for the three cost streams: fuel, variable O&M and fixed O&M.

For now, we have used judgmental estimates of the correlation coefficients along with sensitivity analysis to determine how changes in the estimates affect the resulting portfolio standard deviations. The assumed cross correlation coefficients are given in Table 1-5 and can be interpreted as follows.

It is assumed that for every pair of technologies A and B ( $A \neq B$ ) the following correlations  $\rho_{AB}$  apply:

- The correlation of O&M costs with fuel costs are presumed to be close to zero. Therefore, the correlation of variable O&M with fuel as well as the correlation of fixed O&M with and fuel is set to zero.
- For any two technologies, one would expect a correlation coefficient of 1.0 between the variable and fixed O&M outlays of each. However, since the O&M cost streams also reflect some degree of random or unsystematic risk, their correlation must be less than 1.0. We use a base case

<sup>65</sup> Labour cost data for USA, Germany and Austria; nominal; sector "Electric light & power";

<sup>66</sup> EU data; nominal; sector "industry and services" (excluding "public administration"): quarterly data was annualized according to formula provided in [Ibbotson Associates 1998 p. 110];

<sup>67</sup> US Employment cost index; index data: quarterly data was annualized according to formula provided in [Ibbotson Associates 1998 p. 110];

<sup>68</sup> Eurozone only

<sup>69</sup> "Public Utilities"

<sup>70</sup> "Precision. production. craft. and repair occupations"

estimate of 0.7. To put it differently, we assume as a base case that the correlation coefficient for the O&M costs of any two technologies will be  $\rho_{AB} = 0.7$ .

- The correlation coefficient between variable and fixed O&M is presumed to be low, and is set to 0.1.

**Table 1-5 Assumed cross-correlations for the cost streams of existing generation assets**

		Technology B		
Technology A		Fuel	Variable O&M	Fixed O&M
	Fuel	Table 1-2 <sup>71</sup>	0	0
	Variable O&M	0	0.7	0.1
	Fixed O&M	0	0.1	0.7

### Results using the base case proxy risk estimates

Figure 1-13 shows the portfolio results using the base case proxy risk estimates. Five risky technologies are considered, i.e. gas, coal, oil, nuclear and wind.<sup>72</sup> The figure gives only the efficient frontier; other information is removed in the interest of clarity. The results indicate that when fuel and O&M cost risk is included, the EU-2000 mix is reasonably close to the efficient frontier, as was the case for the simplified fuel-risk only model of the previous section. In addition, even though the efficient frontier now reflects the addition of O&M risk, the relative location of the EU-2000<sup>73</sup> and EU-2010 mixes with respect to each other and the efficient frontier are quite similar to what they were with the fuel-risk-only model of Section 3.2.

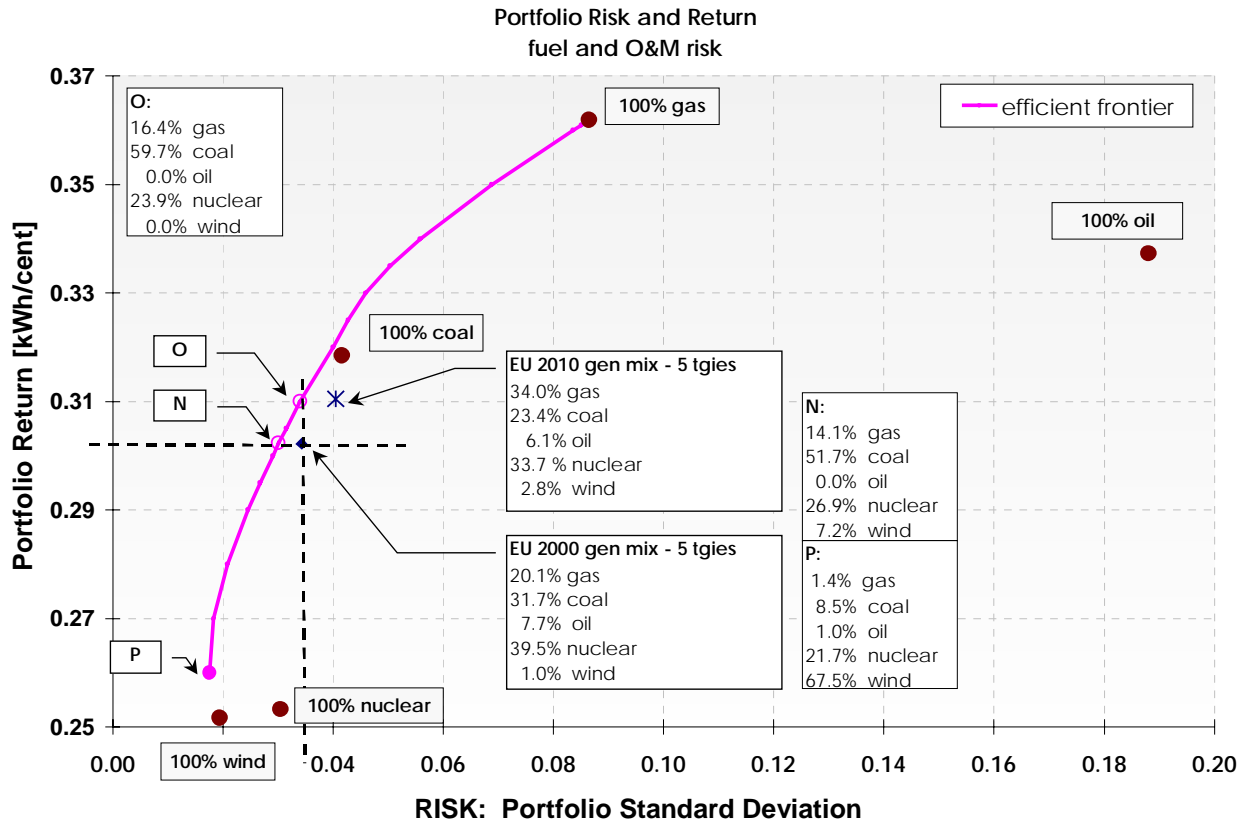
Further, the results indicate that, as before, it is possible to *costlessly* improve on the EU-2000 mix.<sup>74</sup> This can be done by including more wind, which creates portfolios with both lower cost and risk. For example, portfolio *N*, on the efficient frontier, is less risky than the EU-2000 mix but has the same return or generating cost. *N* contains no oil, more wind and coal, and less nuclear and gas generation.

<sup>71</sup> This correlation is calculated on the basis of HPRs of historical fuel prices.

<sup>72</sup> Note that in Electricity Information (2001) wind is added up with “solar” and “tide”. However, since the electricity generation of solar and tide is (and will be) very small compared to wind, it is basically only wind. The 5 technologies make up approximately 86% of the generation mix together [Electricity Information (2001)]. Hydro is excluded from this mix.

<sup>73</sup> Contrary to the preceding sections the EU-2000 mix now contains wind. We included it because with the O&M risk wind becomes a risky asset like the four conventional technologies.

<sup>74</sup> Under the conditions specified before, e.g. zero transaction costs.



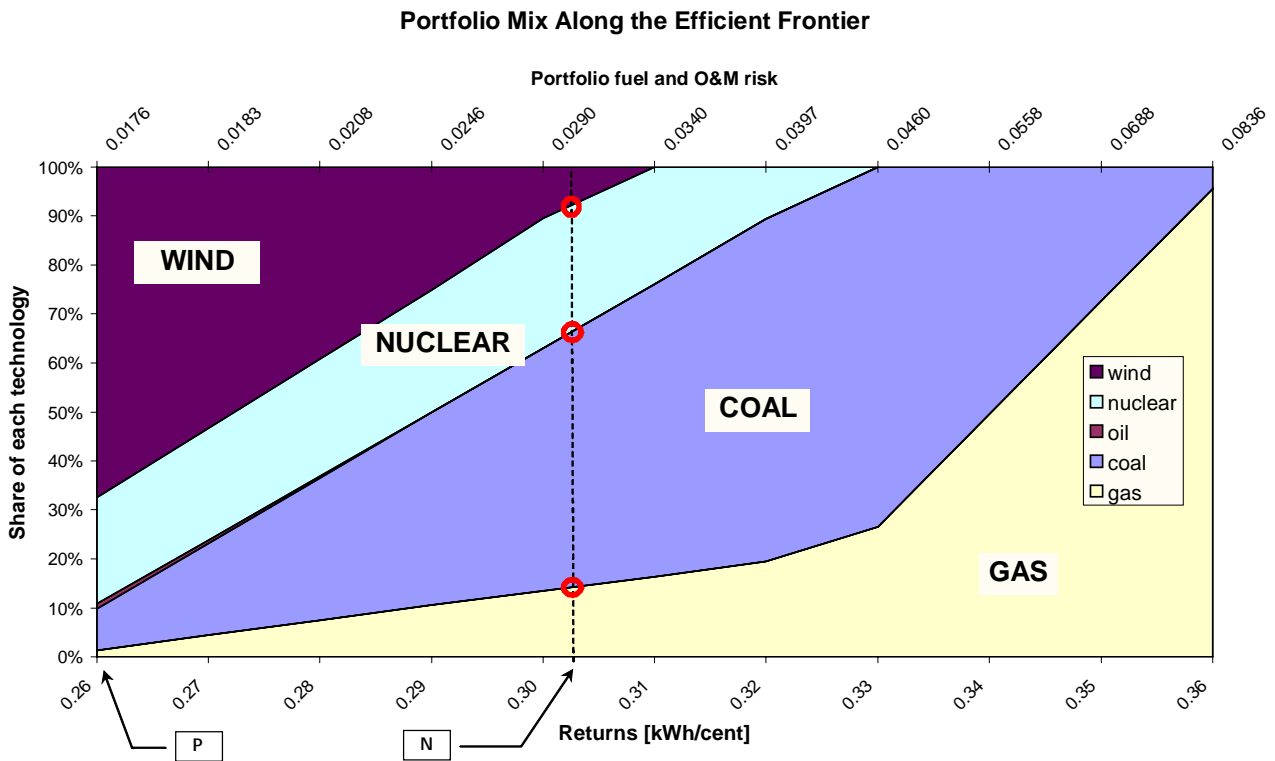
**Figure 1-13 Portfolios of four conventional technologies – fuel and O&M risk<sup>75</sup>**

Alternatively, note portfolio *O* with the same risk as the EU-2000 mix but with lower cost (higher return). Portfolio *O* contains approximately 60% coal, 16% gas and 24% nuclear with no wind. There are other possible portfolios between *O* and *N*, all of which are superior to the EU-2000 mix. Similarly, the projected EU-2010 mix is also inefficient, and can be improved, by moving to e.g. point *O* although this now implies a significant increase in the share of coal (from 23% to 59%) and a decrease in gas, nuclear, and wind. Any increases in the share of wind would now be represented by a move down the efficient frontier, e.g. moving to the 7.2% share of wind represented by portfolio *N* will reduce return or increase cost by 2.5%. When O&M costs are included, the addition of more wind to the EU-2010 mix is not costless, yet, it yields the benefit of reducing risk by about 15.9%. This result changes when new costs estimates for capacity additions as well as construction period risks are included subsequently.

Note that the efficient frontier ends with portfolio *P*, which comprises mainly wind (68%) and nuclear (22%) and only little gas and coal - see also Figure 1-14 below.<sup>76</sup>

<sup>75</sup> When comparing Figure 1-13 with Figure 1-10 portfolio risk in the former seems to be generally higher than in the latter. That is due to the fact that the measurement of risk has now changed. This new scaling will however remain constant throughout the rest of the paper. See also footnote 45.

Finally, Figure 1-14 shows the changes in technology shares as the portfolio mix moves up the efficient frontier from *P* to 100% gas. While significant shares of wind occur at lower risk–return mixes, coal and gas dominate the higher risk–return portfolios. The share of oil never rises above 1.1% while the percentage of nuclear reaches a maximum of 27%, (at risk / return 0.03-0.305), significantly lower than its 40% share in the current EU-2000 mix.



**Figure 1-14 Portfolio mixes along the efficient frontier – fuel and O&M risk**

### Completing the analysis: New and existing generation capacity

Previous sections have presented a range of efficient portfolio solution for the EU. These solutions were based on the assumption that both new and existing capacity has the same set of costs, and that fuel and O&M costs are the only risks. This section extends the analysis and presents a conceptually more sophisticated model that distinguishes between existing and new capacity and hence explicitly models the costs and attendant risks for "new" as well as existing gas, coal and wind capacity.<sup>77</sup> The

<sup>76</sup> Observe that such high shares of wind are of course not feasible since technical potentials according to Huber et al. 2001 limit wind to 7.9% in 2010.

<sup>77</sup> An increased electricity demand is generally met by building new capacity. Electricity produced depends on the dispatch of available capacity, i.e. on annual full load hours of each installed capacity. Since the presented model does not deal with installed capacity but with electricity generated it implies average full load hours.

model now consists of a 7-technology mix, four old technologies — coal, gas, oil and nuclear, and three new ones — wind, gas and coal.

We do not include “new” nuclear capacity additions on the basis of the apparent widespread political climate opposing this technology in Europe (with Finland as the exception). Likewise, we do not include new oil capacity in accordance with the EU-2010 forecast [Electricity Information (2001)]. Finally, since the current share of wind in the EU-2000 mix is so low — less than 1% — we do not differentiate between “new” and “existing” wind, but rather model all wind as new. This allows us to simplify the analysis and presentation without sacrificing much realism.

The current model also does not include decommissioning and salvage costs, or other possible transition costs from current to future portfolios. As a consequence, we speculate that the share of existing technologies in the (feasible) efficient portfolios may be understated while the share new technologies may be overstated [Figure 1-15 and Figure 1-20]. This can be partly corrected by constraining existing capacity so it exactly equals its year-2000 generation in the EU mix [e.g. see: Herbst (1990) p. 307]. We do this for the case of nuclear capacity, arguing that economics aside, it is unlikely that much nuclear capacity will be decommissioned over the next 7-10 years. We compare this "practically constrained" optimum to a more globally efficient, unconstrained set of results which we offer in the spirit of a first-step exploration of the range of efficient solutions.<sup>78</sup>

### **Costs and Risks for New and Existing Capacity**

Distinguishing between existing and new technology allows us to explore a range of more realistic portfolio scenarios. For example, construction period risk affects only new generation. Also, new capacity has different capital and operating costs, which are generally lower. However, to the extent that some new technologies, such as many renewables, are on a steeper learning or cost curve [IEA (2000)], applying the same costs to both new and old generating capacity, as we did in previous sections, likely understates the share of renewables in the efficient mix.

Table 1-6 shows the levelised annual costs for the current and new vintage of generating technologies. The costs are further categorised by cost type - e.g. levelised investment cost, fuel, and fixed and variable O&M.

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<sup>78</sup> We also apply a set of technical or *feasibility* constraints that insure that no additional existing (year-2000) capacity is added to the 2010 mix

**Table 1-6 Levelised annual costs of technologies for new and existing generation capacity**

LEVELIZED COST US cents / kWh	GAS		COAL		OIL <sup>79</sup>	NUCLEAR	WIND	
	Existing CCGT	New CCGT	Steam boiler	New steam boiler			Existing	New
Fixed investment	0.64	0.59	1.24	1.18	0.59	2.26	3.08	2.80
Fuel	1.82	1.75	1.33	1.30	2.08	1.00	0.00	0.00
Variable O&M	0.13	0.13	0.28	0.28	0.15	0.03	0.00	0.00
Fixed O&M	0.18	0.18	0.28	0.28	0.15	0.66	0.89	0.89
<b>Total busbar cost</b>	<b>2.76</b>	<b>2.65</b>	<b>3.14</b>	<b>3.05</b>	<b>2.96</b>	<b>3.95</b>	<b>3.97</b>	<b>3.69</b>
<b>Return (kWh/US cents)</b>	<b>0.362</b>	<b>0.378</b>	<b>0.318</b>	<b>0.328</b>	<b>0.337</b>	<b>0.253</b>	<b>0.252</b>	<b>0.271</b>

The levelised costs in table 1.6 are derived from the IEA World Energy Outlook 2000 (WEO 2000). WEO 2000 is a widely circulated and highly regarded source of current and future energy information.<sup>80</sup> However, in the case of financial portfolios, theory holds that current share prices represent a risk-adjusted present value of all future cash flows. For the time being, we chose to use a traditionally determined and widely accepted set of generating costs such as those produced by the WEO 2000. However, in a subsequent sensitivity analysis (Annex B) we use a set of risk-adjusted generating costs, which generally show that relative to fossil technologies, renewables are considerably more cost effective. The risk-adjusted costs therefore produce efficient portfolios with lower fossil fuel shares.

### **Planning and construction period risks and cross-correlation**

Lumpy technology additions produce numerous construction period risks. Longer planning and construction periods especially increase the likelihood that economic and technological changes will affect cost. In this section we again use the proxy risk measure approach to establish a reasonable set of base-case estimates for construction period risk. Future analyses would undoubtedly benefit from actual project reviews, where they are available, in order to develop potentially better estimates of these risks.

The analysis presented in this and subsequent sections is based on the assumption that construction period costs will fluctuate in a manner similar to the historic fluctuations of a broadly diversified market portfolio (whose beta = 1.0). Based on this assumption, we estimated construction period risk

<sup>79</sup> These calculations are by the authors.

<sup>80</sup> Future costs are computed on the basis of WEO (2000) by means of interpolation.

to be approximately 20% (Table 1-3 page 34). This base case variability is applied to the construction period risk of all lumpy additions: coal, gas, oil and nuclear, although different estimates are used later in the sensitivity analysis. By contrast, wind, PV, and other modular technologies will by definition exhibit little construction period risk [e.g. Hoff (1997), Brower et al. (1997) and Venetsanos et al. (2002)]. For these modular technologies the SD for construction period risk is therefore set to zero.

Finally, estimating portfolio risk requires us to estimate the cross-correlation coefficients between the construction period costs for a given technology and other costs. These estimates are made using the approach already described earlier, (Table 1-5 p. 36). For every pair of technologies A and B ( $A \neq B$ ) a cross correlation coefficient,  $\rho_{AB}$ , is assumed for the linkage between investment and O&M costs (Table 1-7). These are supposed to be quite small — 0.1. Next, as discussed in preceding sections, the correlation coefficient of investment costs for two different technologies is set to 0.7 (Table 1-7). Finally, the empirically derived cross-correlations estimates for the HPRs of fuel prices are given in Table 1-8.

**Table 1-7 Assumed cost cross-correlation when construction period risks are included**

Technology A	Technology B				
	Category	Construction Period	Fuel	Variable O&M	Fixed O&M
Construction Period		0.7	0	0.1	0.1
Fuel		0	Table 1-8 <sup>81</sup>	0	0
Variable O&M		0.1	0	0.7	0.1
Fixed O&M		0.1	0	0.1	0.7

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<sup>81</sup> This correlation coefficient is calculated on the basis of HPRs of historical fuel prices.

**Table 1-8 Empirically derived fuel cross-correlations estimates for existing and new vintage technologies<sup>82</sup>**

	GAS	STEAM COAL	CRUDE OIL	ENRICHED URANIUM	NEW GAS	NEW COAL
GAS	-	0.48	0.46	-0.27	-	0.48
STEAM COAL	0.48	-	0.24	-0.13	0.48	-
CRUDE OIL	0.46	0.24	-	-0.37	0.46	0.24
URANIUM	-0.27	-0.13	-0.37	-	-0.27	-0.13
NEW GAS	-	0.48	0.46	-0.27	-	0.48
NEW COAL	0.48	-	0.24	-0.13	0.48	-

As discussed previously, the total risk or standard deviation associated with new capacity additions is higher relative to existing assets because for the latter group, construction period risks are sunk and hence riskless. On the other hand, new capacity additions often involve newer vintage technologies, which inevitably exhibit technologically driven efficiency gains and cost reductions. These appear as higher expected returns in our construct.

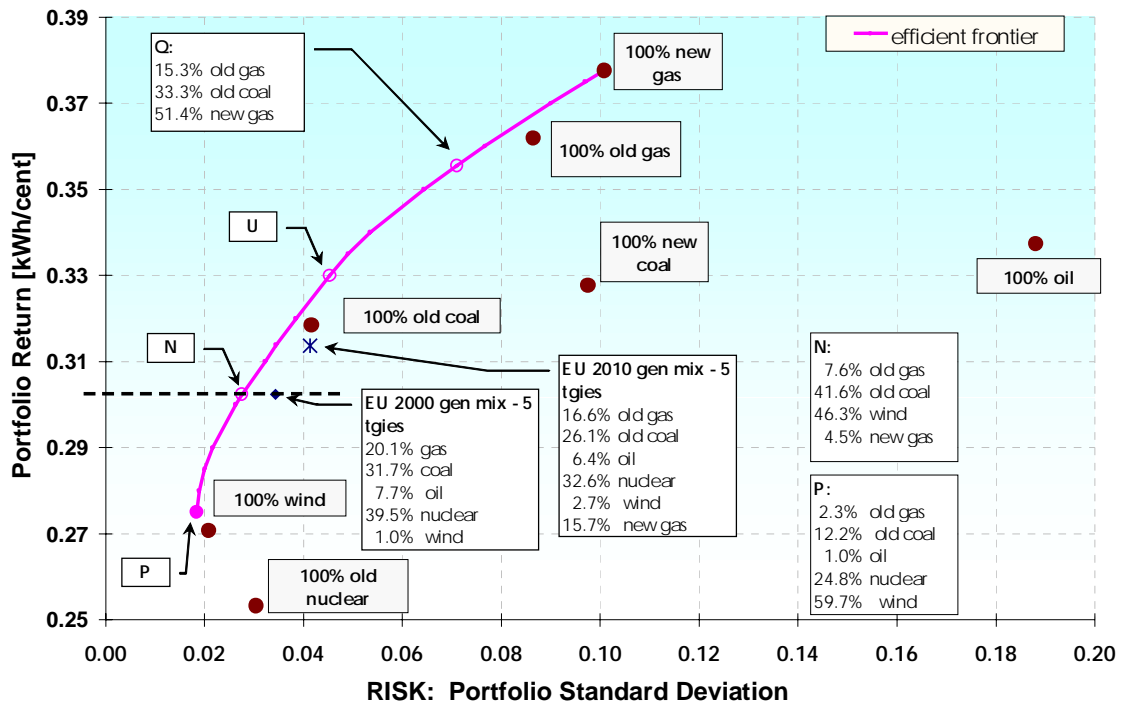
### Base-Case Results

Figure 1-15 shows the base case results. Even though the model is now a much better representation of reality, the basic picture seems to be remarkably similar to the results yielded by the relatively simpler models of earlier sections. This is due to the dominance of fuel price risk on the calculations. Observe that the positioning of the EU-2000 and EU-2010 mixes relative to the efficient frontier and each other is almost unchanged.<sup>83</sup>

<sup>82</sup> Since wind does not exhibit any fuel costs its correlation coefficient with the other technologies is zero and therefore not included.

<sup>83</sup> Note that EU-2000 and EU-2010 are based on different generation levels. While the former corresponds to ca. 2190 TWh, the latter equals 2520 TWh. All mixes shown in the portfolio graph of this section, but the EU-2000 mix, refer to the generation level of EU-2010.

### Portfoliorisk and Return



**Figure 1-15 Base case efficient portfolios: fuel, O&M and construction period risks for existing and new capacity**

As was the case in previous sections, Figure 1-15 suggests that it is possible to costlessly improve the EU-2000 mix by constructing future portfolios such as *N*, with the same costs but lower risk. *N*, which is superior to the EU-2000 mix and hence increases societal welfare, contains approximately 8% old gas, 42% old coal, 5% new gas and 46% wind.<sup>84</sup> Alternatively, policy makers could choose portfolios with lower risk by moving down the efficient frontier to points such as *P*, which comprises 60% wind, 25% old nuclear, some old coal and very small shares of old gas and oil. Similarly the EU-2010 mix can also be improved by moves to the efficient frontier.<sup>85</sup> Although not depicted here, such portfolios would contain added amounts of wind as discussed in subsequent sections.

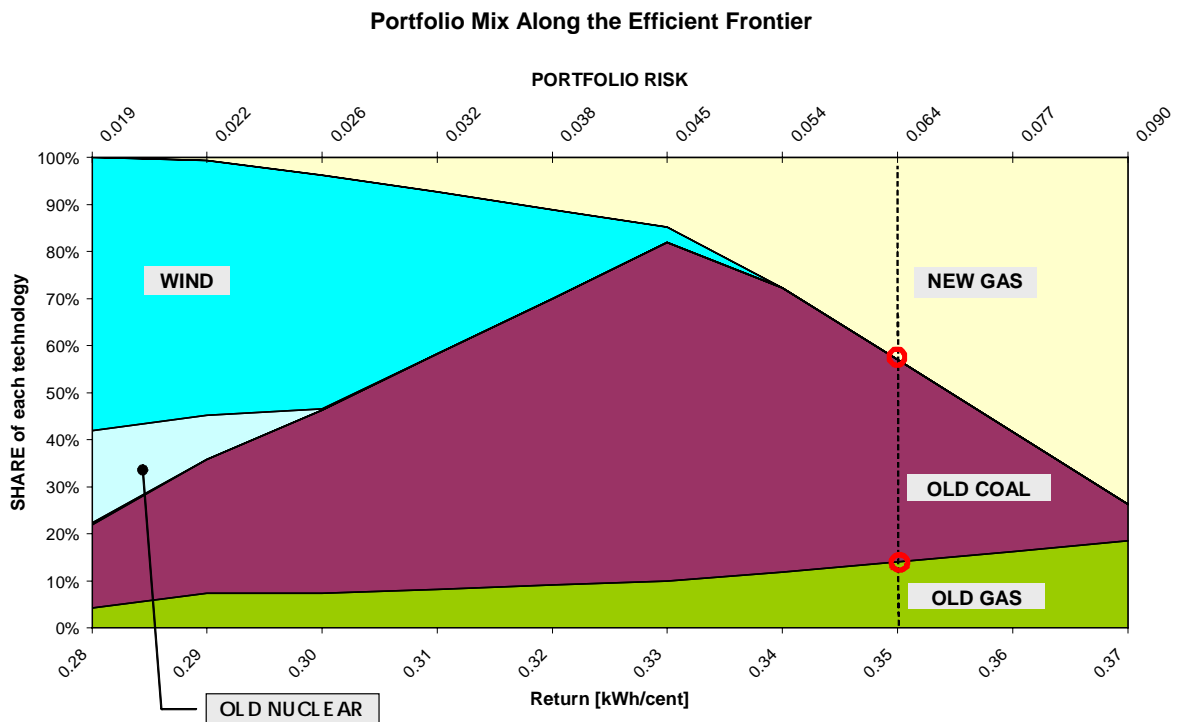
Finally, Figure 1-16 depicts the technology shares at different risk/return levels, which help policy makers understand the required technology trade-offs for moves along the efficient frontier of Figure 1-15. Interestingly and somewhat surprisingly, the efficient frontier contains no “new coal”. This

<sup>84</sup> Note that such high shares of wind are of course not feasible since technical potentials according to Huber et al. 2001 limit wind to 7.9% in 2010.

<sup>85</sup> Observe that while EU-2010 includes new and old gas, coal, oil, nuclear and wind, from a mean-variance perspective it lies very close to, and hence could be replaced entirely by a single technology— old coal.

comes from the fact that “new coal” exhibits the highest investment period risk because its share of investment costs (see Table 1-6) is the highest among the new non-modular technologies.

At lower risk/return levels, wind and old coal dominate the mix, while for high risk–low cost (high return) portfolios, the efficient mixes consist primarily of new and old gas and some old coal. At return levels above 0.30 kWh/cent nuclear is no longer contained in the mix (see line in Figure 1-16).



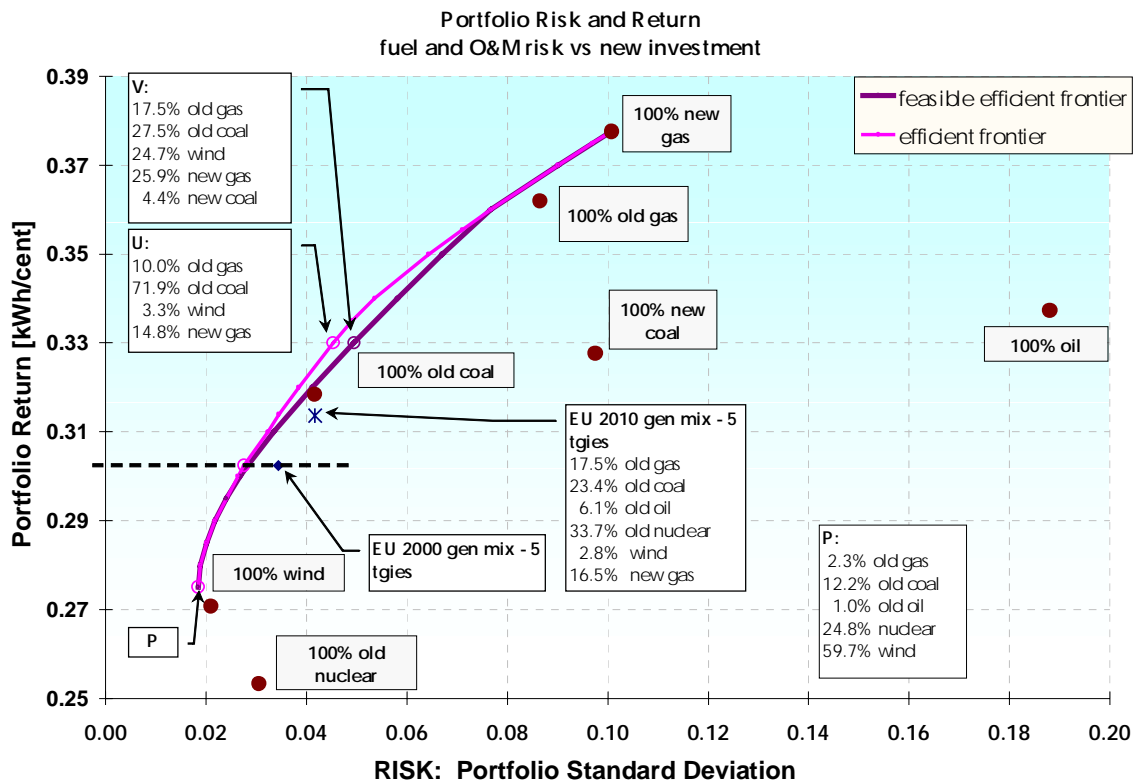
**Figure 1-16 Portfolio mix along the efficient frontier: fuel, O&M and construction period risks for new and old capacity**

### Technical Feasibility of the 2010 Portfolios

Compared to the EU-2000 generation mix, the projected EU-2010 mix exhibits a higher risk coupled with higher return (Figure 1-15). While some may prefer this risk-return combination, it cannot be said to be economically superior to the EU-2000 mix. This can be understood by illustration: some people prefer to invest in riskier stocks while others like bonds, but neither of these is "superior" or more efficient. In fact, the increased return (cost reduction) of the EU-2010 almost exactly equals its percentage risk reduction.

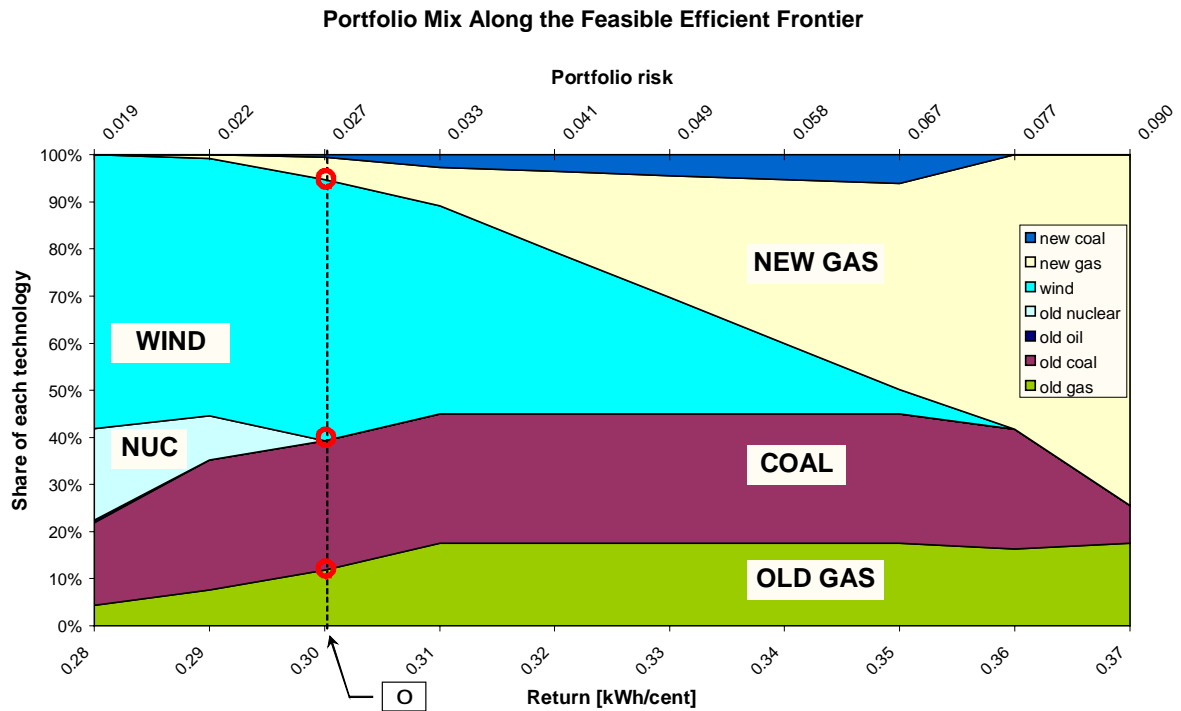
Moreover, the projected EU-2010 mix is inefficient. It does not lie on the efficient frontier, though it comes close, indicating that better portfolios such as U (Figure 1-16) exist. These would likely include higher shares of old coal (71.9%) along with a higher share of wind. However, a share of almost 80% of “old coal” in an EU 2010 mix is of course not feasible.

Feasible solutions can be obtained by constraining the shares of existing technologies in the efficient frontier so that they cannot exceed their actual EU-2000 generation. Therefore, for example “old coal” does not exceed a share of 27.5% in the mixes for 2010. This produces efficient solutions (Figure 1-17) that are technically feasible. Such solutions lie along what we term the *feasible efficient frontier* (FEF). Observe that the FEF lies just slightly to the right of the efficient frontier. Points *U* on the efficient frontier and Point *V* on the FEF produce the same expected return but *V*, on the FEF, exhibits 7.3% more market risk. Compared to Portfolio *U*, *V* contains more wind (25% vs. 3%), old gas (18% vs. 10%) and new gas (26% vs. 15%) as well as some new coal (4%).



**Figure 1-17 Efficient feasible portfolios: fuel, O&M and construction period risk for existing and new capacity**

Figure 1-18 shows the portfolio mix along the FEF. Since “old coal” is limited to its actual EU-2000 generation – corresponding to 27.5% in the 2010 mixes - other technologies replace “old coal” at return levels where this limit is exceeded. At point *U* (0.33 kWh/cent) coal attains its maximum share (71.9%) of the efficient frontier (see Figure 1-17). In the FEF the exceeding 44.4% “old coal” (71.9% minus 27.5%) are replaced primarily by wind, some gas, “new coal” and “new gas”. Note that “new coal” is a new entrant to the FEF and attains a maximum share of 6%.



**Figure 1-18 Portfolio mix along the feasible efficient frontier – fuel, O&M construction period risk**

### The Effect of practical constraints on the efficient solutions

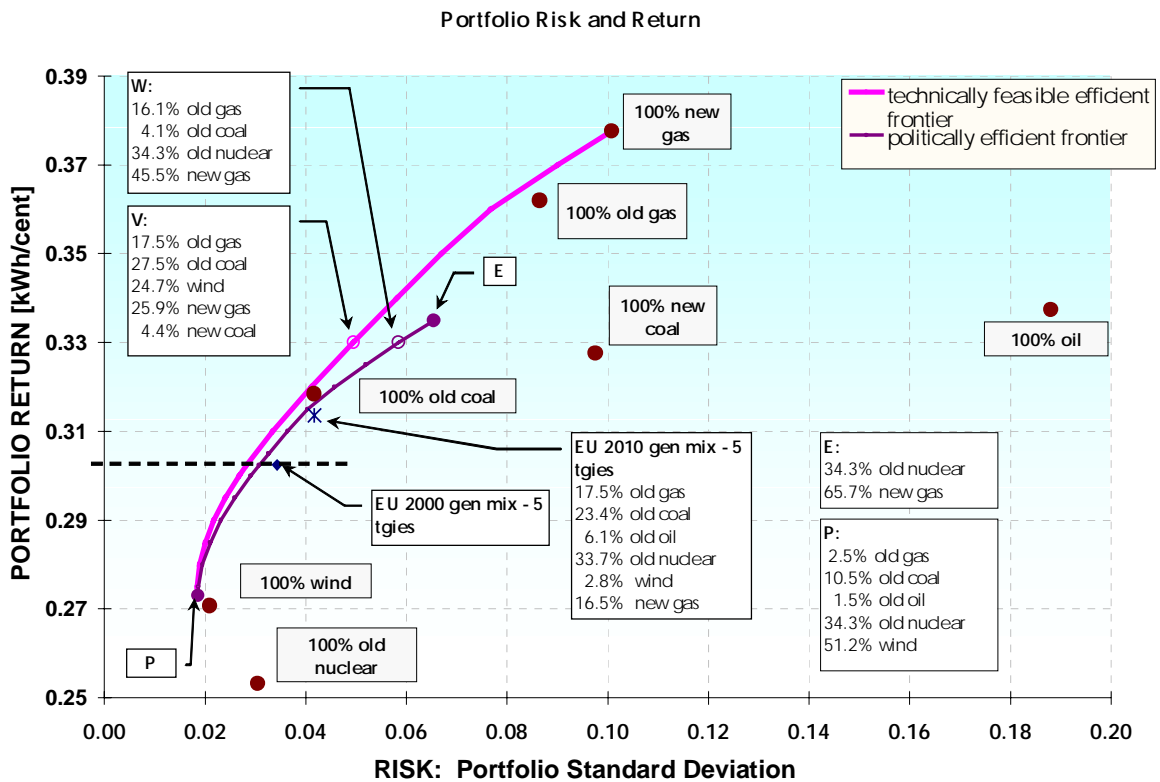
The feasible efficient portfolios presented in the last section contain 0% nuclear at returns in excess of 0.30 kWh/US cent, see mix *O* in Figure 1-18. A 0% nuclear share is obviously not a politically or practically feasible solution for any 2010 portfolio, since it is inconceivable that the vast European nuclear capacity could be dismantled in the next seven years. This solution occurs because, as discussed above, the current formulation of the model contains no decommissioning costs and hence abandoning existing nuclear is costless — which does not hold in reality. Eliminating nuclear from the EU-2010 portfolio would require major decommissioning outlays, which are also *a priori* risky. Future versions of the portfolio model will include nuclear decommissioning and retirement costs for other technologies. This will produce solutions that are more "practically feasible".

However, practical efficient portfolios can be *approximated* by constraining nuclear generation to its actual generation level<sup>86</sup> so that it maintains its 34.3% share of the EU-2010 mix. This produces solutions that are more reasonable with respect to nuclear capacity. These solutions lie along what we call the *practical efficient frontier* (PEF).

<sup>86</sup> This is in addition to the constraints introduced for the feasible efficient frontier in the last section.

Constraining nuclear has important effects so that the PEF differs significantly from the FEF as illustrated in Figure 1-19. The PEF clearly moves to the right, so that it just about passes through the projected EU-2010 mix, as might be expected. Point V on the FEF produce the same return as W, on the PEF, but W exhibits 18% more market risk. This might be one measure of the economic cost associated with the practical constraints. Compared to portfolio V, W contains significantly less old coal (4.1% vs. 27.5%), more nuclear (34.3% vs. 0%), more new gas (45.5% vs. 25.9%) and no wind.

Second, constraining nuclear as we did severely reduces the maximum portfolio return levels compared to the technically feasible solution (Figure 1-19). While the maximum portfolio return of the FEF is the same as the return for new gas, i.e. 0.378 kWh/cent, the maximum return of the PEF is only 0.335 kWh/cent (point E in Figure 1-19). This might be another measure of the cost of the practical constraint. Observe that point E consists of 34.3% nuclear and 65.7% new gas.<sup>87</sup>

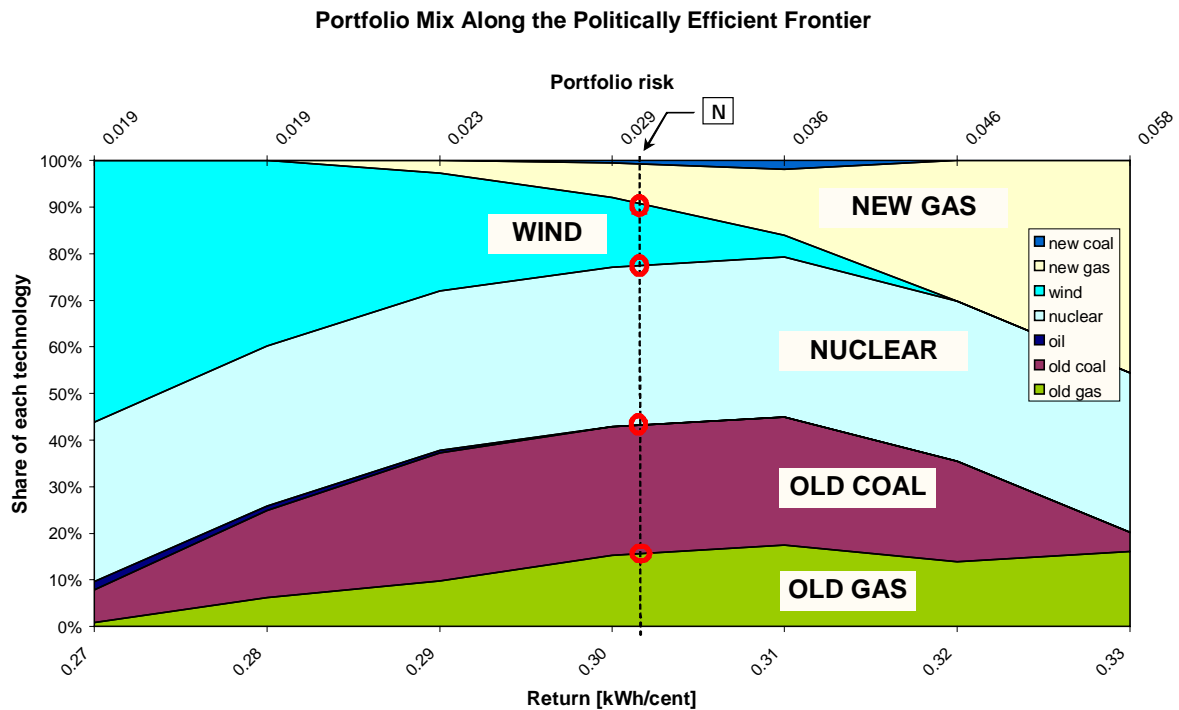


**Figure 1-19 Efficient practically feasible portfolios: fuel, O&M and construction period risk for existing and new capacity**

<sup>87</sup> We are of course aware of the fact that only approximately 10% of the generating capacity will realistically change till 2010. Therefore, extreme solutions, such as a mix of 34% old nuclear and 67% new gas, are not practically feasible. However, we did not exclude these solutions from the politically efficient mixes a priori.

Figure 1-20 shows the portfolio mix along the PEF. Since nuclear is constrained to its actual generation its share rests constant over the whole PEF. This is mainly at the expense of wind but also of old coal at higher return levels.

The actual EU-2000 mix can, as before, be improved by introducing wind into the mix. At the same return level as the EU-2000 mix, i.e. 0.302 kWh/cent (mix *N*), the efficient solution would contain 17.1% old gas, 27.5% old coal, 34.3% nuclear, 12.2% wind, 7.7% new gas and 1.2% new coal.



**Figure 1-20 Portfolio mix along the practically efficient frontier – fuel, O&M and construction period risk**

Explicitly differentiating between existing and new capacity presents results that comport more closely to real-world issues currently confronting EU policy makers. These issues include the type and share of various technologies and the potential replacement, curtailment or abandonment of certain technologies.

While the analysis deals with these issues explicitly, it ignores the risks and costs of salvage and decommissioning, which may be particularly significant in the case of nuclear power plants. While the results presented seem useful and realistic, additional analysis that reflects decommissioning and other costs and risks may further improve the practically feasible results presented here. However, while decommissioning costs are not explicitly included, we have approximated the equivalent practically feasible solution by constraining the nuclear share to its year-2000 generation level. This has significant effects on the portfolio and severely reduces its return levels compared to the technically

feasible solution. It yields a set of practical solutions that illustrate the economic costs of political policies.

### Summary of important results

Our results clearly suggest that energy policy makers in Europe and elsewhere need to consider the implications of mean-variance portfolio analysis as an input to various energy policy making and planning processes. These policy makers are currently confronting a number of important energy policy issues:

- i. **Energy Security:** While energy security is widely taken as synonymous with avoiding large-scale fuel disruptions, we have characterised a more subtle, and, we believe, highly significant aspect of this issue: minimizing costly fossil-driven electricity price fluctuations. The prospect of wide-scale fuel supply disruptions is certainly costly and unappealing. Yet day-to-day fuel price increases and volatility is quite costly as well, creating economic losses that can easily run into the tens and hundreds of billions.<sup>88</sup>
- ii. **Energy diversity:** Like energy security, energy diversity objectives are generally not defined explicitly, although the commonly accepted objective *seems* to involve creating robust energy mixes — i.e. efficient portfolios — that will minimize price risk under a variety of possible outcomes.
- iii. **Affordable and Reliable Electricity Costs:** Creating an affordable electricity supply involves creating portfolios with known expected price and risk characteristics. These portfolios must reliably supply electricity in the sense of offering reasonable (affordable) long-term price streams with reasonable volatility.

Mean-variance portfolio optimization addresses precisely these types of issues. For example, insuring energy security (Item i) may involve a number of factors, including the diversification of supply away from sources that may be politically unreliable. However, it is equally important to insure that the European generating portfolio is efficient in the sense that it minimizes price risk (volatility) exposure at any given cost level. Portfolio theory represents the only quantitative means for evaluating portfolio efficiency, which also insures that energy diversity (Item ii) and affordability/reliability (Item iii) objectives are implemented.

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<sup>88</sup> A summary of the literature is given in Sauter and Awerbuch (2002). The recent literature seems to suggest that fossil price volatility itself, especially to the extent that it creates price "surprises", is as important as energy price increases in reducing economic GDP growth.

In general, our results indicate that the current and projected EU generating mixes are inefficient or sub-optimal from a risk-return perspective. The analysis further indicates that portfolios with lower cost and risk can be developed by adjusting the conventional mix and by including larger amounts of wind or similar fixed-cost technologies. More specifically, the results suggest that increasing the share of wind and similar fixed cost renewables in the generating mix up to levels of 12% does not increase overall portfolio generating costs as compared to the year-2000 EU mix. Under some circumstances, additional portfolio shares of renewables even serve to *reduce* overall cost and risk. This result, which holds under a wide variety of assumed conditions, runs contrary to most analyses and to widely held conception that given their higher stand-alone costs, adding renewables to the conventional mix can only serve to increase overall generating cost.

While specific risk (as measured by the standard deviation of HPRs) and cost results vary as the input assumptions, included risks and other conditions, are changed, the overall portfolio picture is remarkably robust so that the basic message — that the addition of fixed-cost renewables generally reduces overall cost and risk — changes little.

Finally, the effect of practical constraints on the optimal solution are modelled. This is done by constraining certain technologies, in this case nuclear, to their Year-2000 generation under the assumption that nuclear capacity will not be decommissioned over the next 7-10 years. This produces a practically efficient frontier (PEF) and a set of practical-efficient solutions. While these are generally inferior to the technically feasible solutions produced previously, they can still be improved with the addition of fixed cost technologies such as renewables.

## **Conclusions**

This analysis applies mean-variance portfolio optimization techniques to evaluate the efficiency of current and projected EU generating mixes and to develop alternative portfolios with lower cost and risk. The results generally indicate that the existing and projected EU generating mixes are sub optimal - though slightly - from a risk-return perspective, which implies that feasible portfolios with lower cost and risk exist. These can be developed by adjusting the conventional mix and by including larger shares of wind or similar renewable technologies.

The results of the portfolio analysis suggest that fixed cost technologies such as renewables must be a part of any efficient generating portfolio. Our assessment of all technologies is limited to risk and cost measures, although other benefits, including low externality costs and sustainability, are often cited for renewables.

The analysis began with a relatively simple portfolio model. Though it included all operating and capital costs, this model reflected only a single risk — fuel cost risk. This risk is empirically estimated on the basis of the historic holding period return (HPR) for fossil and enriched nuclear fuel. A striking characteristic of the fuel risk-only-model is that the efficient frontier includes a straight-line segment representing various mixes of wind and the conventional portfolio. This line segment exists because wind has no fuel costs so that the standard deviation and the correlation coefficients for fuel are reduced to zero, which produces a straight line.<sup>89, 90</sup> On the risk axis, this line segment lies to the left of the feasible set of conventional mixes, indicating that the inclusion of wind serves to reduce cost and risk.

### **Implications for the EU Portfolio**

Models that reflect the risk of fuel as well as the risk associated with fixed and variable O&M are then introduced. This allows a more realistic evaluation of the current EU year-2000 portfolio. Specifying O&M risk requires that the cross-correlation coefficients between wind and the conventional technologies are specified. Since wind exhibits O&M risk, the O&M standard deviations and cross correlations are now non-zero, so that the straight-line segment of the efficient frontier becomes a curved segment along which lie all the possible efficient mixes.

The additional O&M risk that is now included serves to increase the overall risk. However, this increase affects wind as well as the conventional technologies so that the principal message remains largely unchanged: adding wind to the year-2000 and the projected year 2010 mixes might serve to reduce cost and risk.

The standard deviations for the fixed and variable O&M costs are then estimated using financial proxies, although future work may well benefit from an empirical analysis of the volatility of actual historic O&M costs for different generating technologies. Financial proxies are used because appropriate historic O&M cost data are not available. Under the approach fixed O&M costs are "debt-equivalents" while the risk of variable O&M costs is similar to the risk of the market as a whole. Such procedures are often used to estimate risk and discount rates in financial analyses.

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<sup>89</sup> Recall that Equation 1.2, which is the expression for portfolio risk, reduces to a straight line when one of the variances (e.g.  $\sigma_1^2$ ) is set to zero. Portfolio return is also a linear function of the portfolio shares and their returns.

<sup>90</sup> The choice of renewable technology affects the straight-line segment. For example, if the renewables technology were to consist of only PV, which has virtually no operating costs, the lower end of the efficient frontier, reflecting 100% PV, will lie much closer to the vertical axis where SD = 0.0.

In the case of the existing year-2000 portfolio, construction period risks are not relevant. Projected capacity additions however, will exhibit construction period risks as well as operating risks. In order to more fully evaluate the projected 2010 EU generating mix, a more complex model that includes planning and construction period risks is added to the fuel and O&M risks included in the previous analyses. This enhanced model distinguishes between existing capacity and capacity additions, e.g.: "existing" versus "new" gas and coal.

Total risk in the case of existing capacity consists of the fuel and O&M risks; in the case of new coal and gas planning and construction period risk is also included. Wind and similar modular technologies are characterised by short construction periods with short planning lead times, which minimizes or essentially eliminates uncertainty during this period. In the case of wind, therefore, risks are the same for existing and new vintages. Finally, although construction period costs are sunk, they are part of the total cost estimate for both new and existing technologies since they are recovered through annual charges.

By distinguishing between the projected costs of new technology vintages as compared to existing vintages, the enhanced model also allows us to incorporate technological progress. Capital and O&M costs for capacity additions are typically lower than the capital and O&M costs of existing vintages. The enhanced model provides a more realistic representation of the existing and projected EU generating mix. It uses new, lower projected costs for the capacity additions as compared to existing capacity vintages.

The enhanced model can examine the effect of practical constraints on the optimal solutions by developing what we term *practically efficient solutions*. For example, independent of underlying economics of the mix, it seems highly unlikely that any nuclear capacity will be decommissioned between now and the end of the decade. This constraint is included to produce a set of practical - efficient solutions by limiting future nuclear generation to its generation in the EU-2000 mix. This permits comparison of the practical - efficient solutions to the unconstrained or technically efficient solutions. Constraining the nuclear generation as described has striking effects on the portfolio and severely reduces its return levels compared to the technically feasible solution.

Though it reflects a much broader range of risks and other factors, the enhanced model continues to support the basic message of the simple fuel-only model: i.e.: the year 2010 projected EU mix is less than efficient. The mix can be made more efficient by adjusting the conventional technologies, and, depending on the risk-return preferences, by adding renewables. Stated differently, it is possible to improve the projected 2010 mix without adding more renewables, however, increasing the renewables

share in many instances costs no more and reduces risk.<sup>91</sup> Since environmental and other externality benefits of renewables are not considered, this result can be seen as an additional benefit of adding renewables to the generation mix.

As a corollary, it can be observed that current national policies that focus on gas expansion to the exclusion of fixed cost technologies are inappropriate. In some instances, such policies will only serve to increase risk disproportionately to any attained cost reductions. Gas expansion should not be implemented in an economically efficient manner without a simultaneous national focus on expanding the share of “riskless” technologies like renewables to counter the increased risk of gas.

The basic finding of this analysis therefore seems quite robust, and does not materially change even when the risk parameter estimates are changed significantly in the sensitivity analysis. More precisely, the sensitivity analysis alters the overall risk of the resulting portfolio, but does not change the relative location of each alternative on the graph, nor does it materially change the shape of the efficient frontier.

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<sup>91</sup> Note that no transition costs are considered in the present model.

## Annexes

### Annex A: Assumptions and Limitations Affecting the Application of Mean-Variance Techniques to Generating Portfolios

This paper explores the application of mean-variance Markowitz portfolio theory, originally developed for financial assets, to the creation of optimal portfolios of generating asset. This application rests on a set of explicit and implicit assumptions and limitations that are discussed below:

1. **Indivisibility of assets:** “The mean-variance portfolio model is based on the assumption that securities are infinitely divisible, while capital investments often come in very large, indivisible units [Seitz (1990) p. 233].”<sup>92</sup>

Our model therefore implicitly relies on the assumption that for the analysis of large service territories or national generating portfolios, the lumpiness of capacity additions becomes relatively less significant since total capacity needs are larger.

2. **Normal distribution of holding period returns:** “By looking only at mean and variance, we are necessarily assuming that no other statistics are necessary to describe the distribution of end-of-period wealth. Unless investors have a special type of utility function (quadratic utility function), it is necessary to assume that returns have a normal distribution, [Copeland and Weston (1988) p. 153].” For our analysis, it remains to be determined whether the fuel price HPRs are actually normally distributed. However, fossil fuel prices are commonly modeled as *random walks*,<sup>93</sup> [see e.g. Felder (1994), Hassett and Metcalf (1993), Holt (1988), Glynn and Manne (1988)], which implies that price changes are at least independent.

3. **Perfectly fungible assets:** Portfolio assets must be perfectly fungible: their value at any point in time must depend only on the amount, timing and certainty of expected cash flows.

This may not always hold for generating assets where issues such as location and fuel availability may affect selection for various reasons. Location may therefore affect asset value to the extent that existence of, for example, a nearby gas line, may enhance the “amount, timing and certainty” of cash flows only if a gas plant, (as opposed to a coal plant) is constructed. Technology choice may further affect asset value to the extent that electric grid connection, siting and similar costs may differ for different technologies.

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<sup>92</sup> See also Herbst (1990) p. 303.

<sup>93</sup> *Random walks* require all the parameters of a distribution to be the same with or without an information structure. “Furthermore, successive drawing over time must (1) be independent and (2) be taken from the same distribution.” - [Copeland and Weston (1988) p. 348]. To put it differently, yesterday’s prices cannot be used as a basis for predicting future prices.

4. **Taxes and subsidies:** Our analysis is primarily intended for public policy making and hence deals with cost risks to society as a whole (or at least to all EU electricity consumers). We therefore view taxes and subsidies as transfer payments, which should properly be ignored in this context.
5. **Past as a guide to the future:** Portfolio theory uses past volatility as a guide to the future.<sup>94</sup> We rely on nominal annual data for the estimation of the variability of fuel price HPRs in order to exclude seasonal fluctuations from our risk appraisal.
- However, some argue that risk, properly defined, is a measure where “a probability density function may meaningfully be defined for a range of possible outcomes [Stirling (1994)].” Given this definition our focus is on (probabilistic) total risk, which will still not reflect possible future ‘surprise’. This, therefore, suggests that there may still lurk surprises out there that cannot and have not been reflected by our historic SD estimates,<sup>95</sup> and which may someday cause an unexpected discontinuity. We, however, choose to focus on that which is probabilistically tractable.

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<sup>94</sup> This is underpinned by e.g. Ibbotson Associates (1998) p. 27, Harlow (1991) p. 33, Sharpe (1970) p.179

<sup>95</sup> One of the reviewers, Professor John Byrne, argues as follows: The SD measure does not prescribe any particular underlying probability distribution. We model events that can be logically and empirically treated as probabilistic risk. There are other events, not in our model, that can be analysed, but not with probability theory. G.L.S. Shackle, [*Epistemics and Economics*, Cambridge: Cambridge University Press, 1972], stresses this distinction, and identifies three rules necessary for the meaningful calculation of SD: i) the *completed list rule*, ii) the *frequency rule* and iii) the *cumulative density rule*.

The three rules presume that events have regular patterns. Probability theory builds on these regularities to assess risk. However, some events are experienced as ‘surprises’ with no comparability or pattern to other events. We experience these events as ‘novel’ and do not try to assess their value in relation to past ones (or conceivable ones for the future). These events and their impacts on the future may not fit the probability model.

However, this reviewer also concludes that Shackle’s idea of ‘surprise’, does not affect our mean-variance analysis. He argues using the following example:

Assume that we have become accustomed to major fossil fuel price variations over a 3-5 year period. We cannot know exactly when and by how much fossil fuel prices will change, but, using past experience, (and including some other conceivable scenarios as well), probability theory can help us understand the range of magnitudes that we might experience.

This would involve probabilistic risk: we assume that variation in prices can be understood to occur within a definite boundary (Shackle’s *completed list rule*), some price increases are more likely than others (the *frequency rule*) and the sum of the probabilities of all variations is one (the *cumulative density rule*).

But a price change either outside that experience range or one that is brought on by unimagined events, e.g. a cartel being able to act in concert for an extended period against all prediction and outside political/economic pressure may cause us to re-think fossil fuel use in a manner that is unrelated to its historic probability, or the variation in prices it caused. The latter roughly qualifies as Shackle’s idea of surprise and novelty. [Source: John Byrne, personal communication]

6. **Expected returns:** Expected returns are based on traditionally estimated levelised generation costs taken from WEO (2000).<sup>96</sup> Our analysis is cost-based, since from a societal perspective, generating costs and risks are properly minimised. Our analysis is therefore not based on revenues from electricity sales, renewables' feed-in tariffs or the price of conventional electricity. Since the expected portfolio returns are cost-based, variations in electricity market prices are not relevant. Financial returns generally reflect a benefit divided by an input, where both are dollar-dimensioned: i.e. "dollars-returned/dollars invested. The financial return measure is therefore dimensionless, a property that does not hold for our cost-based return measure: kWh/cent, which becomes dimensionless only if a monetary value is assigned to the numerator. Multiplying our cost-based portfolio returns, [kWh/cent], by the price of electricity [cent/kWh] yields a dimensionless measure of return that is precisely analogous to the financial measure of return. This procedure however raises questions regarding the appropriate electricity price to use. Electricity markets exhibit short-term price fluctuations driven by strategic behaviour of market participants as well as random daily events including generator outages, weather extremes, etc. Using instantaneous or even daily market prices would improperly introduce additional risk to the portfolio. A relevant, dimensionless return measure for our purposes would be based on an averaged cost from WEO (2000) as representative of long-term equilibrium electricity market prices.<sup>97</sup>
7. **Decommissioning, salvage and transition costs:** Decommissioning and salvage costs, as well as transition costs from the actual to a future portfolio are not included in the current model formulation. The share of new vintage technologies in our *efficient practically feasible portfolios* may therefore be systematically overstated, (see Figure 1-19 and Figure 1-20).
8. **Fuel Cost Data:** Generator owners tend to buy fuel through spot purchases and various contracts, so that the periodic "cost" of fuel in any calendar period is best measured as the total fuel outlays for the period divided by total fuel delivered during the period. Such data is available through historic, country-based time series, which are aggregated from reports from individual EU power plants. The IEA collects country data regarding cost and quantity of fuel delivered to power plants, but the data is quite spotty. We therefore used fuel import data, obtained from WEO (2000) for IEA Europe<sup>98</sup> and supply data from ESA (2000). For the final

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<sup>96</sup> A sensitivity analysis is performed in Annex B using risk-adjusted costs developed in Awerbuch (2002).

<sup>97</sup> Or from Awerbuch (2000). Unlike WEO (2000), Awerbuch's risk-adjusted cost estimates reflect tax credits and depreciation allowances. However, both sources ignore external costs.

<sup>98</sup> Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

results the estimations of SD and correlations are based on a time series of 12 years for each conventional fuel (1989 to 2000).

- 9. Financial proxies:** As discussed in the section entitled “A proxy method for estimating O&M risk”, we used financial proxies to derive estimates for all but the fuel-price risk. We had no access to historic project data covering O&M costs.<sup>99</sup> In the case of construction period costs and risks, public data is also difficult to find although many firms do track expected and actual project planning and construction costs.
- 10. "Fuel risk" for fixed-cost renewables like wind:** We are aware of the fact that fluctuations in renewable electricity generation due to e.g. variable wind availability can cause additional *opportunity costs*. These opportunity costs bear risk since often risky sources, i.e. fossil fuels, serve as backup. In this analysis we assume that there is no backup capacity necessary in addition to the existing. We do not take into account any opportunity costs - and hence risk - for wind electricity generation. Considering the EU electricity grid to be ONE grid and given that the year 2010 mid-term potential is approx. 7.9% of the EU-2010 electricity generation [Huber et al. 2001] this assumption is underpinned by studies claiming that wind penetration levels of 5% to 10% cause little or no change in the current operation strategy [Wind Energy Weekly (1996), ERU (1995)].

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<sup>99</sup> While they would provide actual historic cost variability, such data would necessarily raise issues regarding fixed and variable costs and their relationship to output. This may require altering the commonly used cost categories.

## Annex B: Sensitivity analyses

While our proxy-based variability estimates for O&M and construction period costs have some financial justification, they are to some extent arbitrary. We therefore tested the effect that changes in these estimates have on the efficient frontiers through a series of sensitivity analyses, as discussed below.

Sensitivity analysis was performed for the base-case and technically feasible portfolios of Section 3.4, which include existing as well as new capacity. The analysis comprised a

- a. Variation of cost stream risk, i.e. their HPR standard deviations (SD) – (see Sections 3.3 and 3.4),
- b. Variation of their cross-correlation (see Table 1-7 p. 41); In addition, an analysis is performed with
- c. Risk-adjusted costs.

The sensitivity analysis focuses on reductions in the correlation coefficients and cost variabilities. We do not explore increases in these two variables because indications are that they have already been estimated on the high side. For example, the SD of labour costs (Table 1-4) is for the most part, significantly lower than our estimated SD of 8.7% and 20% for fixed and variable O&M respectively. Likewise, the principal base-case correlation coefficient are set at 0.7, which we feel is quite high, given an upper limit on this variable of 1.0.

### **B-1. Sensitivity analysis of the standard deviations**

The first part of the sensitivity analysis explores the effect of reducing the estimated variability for the three non-fuel cost streams. Subsequent sections deals with the correlation coefficients between technologies and risk-adjusted costs.

Sections 3.4 and 3.5 discussed the volatility estimates for the three non-fuel cost streams. We did not have access to historic data for these streams – and hence used financial proxies to develop estimates of their variability. Specifically, we assumed that the variability of fixed O&M costs could be treated as a debt-equivalent whose standard deviation is the same as the historic SD of long-term corporate bonds (see Table 1-3 p. 34). The risk of variable O&M and construction period costs was taken as the overall market risk of a broadly diversified portfolio with  $\beta = 1.0$  (Table 1-3). The base case and sensitivity values for these SDs are given in Table 1.B-1.

Table 1B- 1 Standard deviations of the cost streams used for sensitivity analysis

Standard deviations	Base Case	Alternate Case
Investment period	20%	8.7%
Fuel	estimated for each technology	
Variable O&M	20%	8.7%
Fixed O&M	8.7%	3.0%

The resulting efficient frontier (Figure 1B -1) has not significantly changed in shape but has moved to the left. At lower return levels the relative difference is more important than at higher return levels (Table 1B-1).

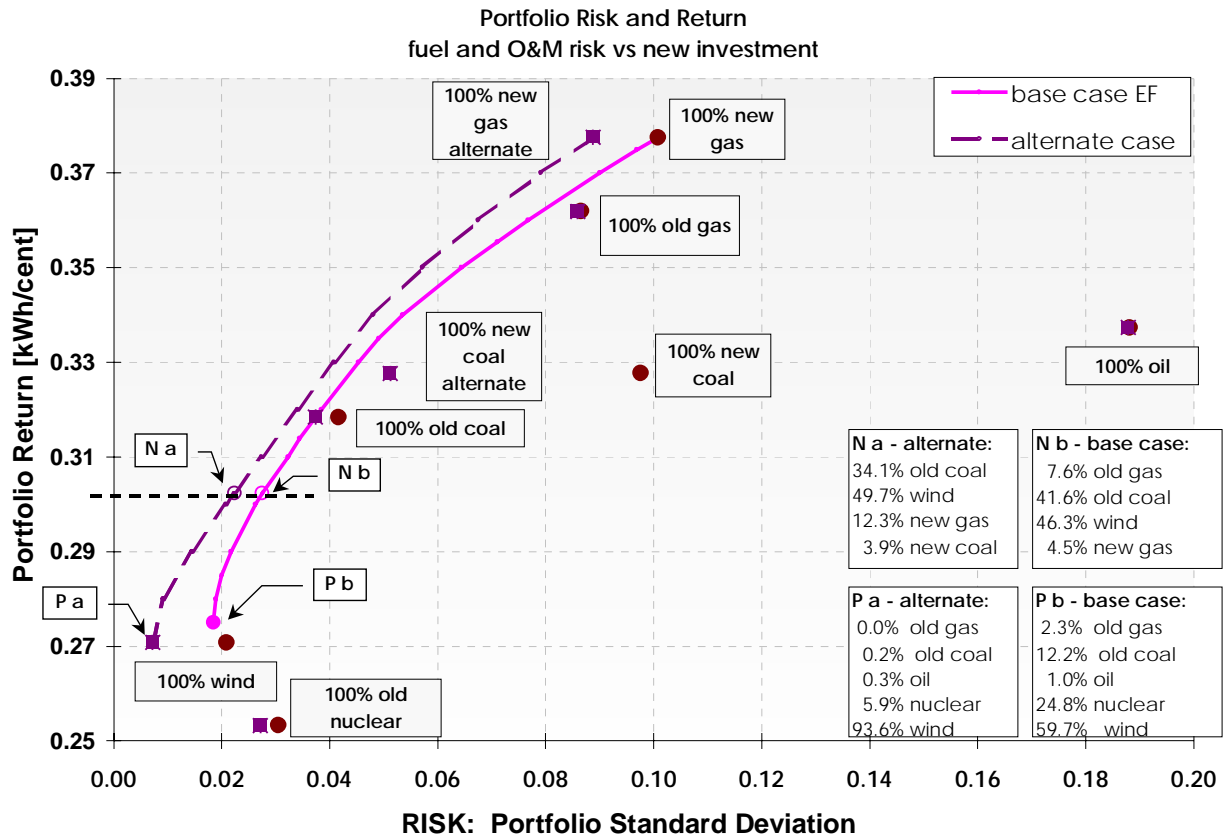
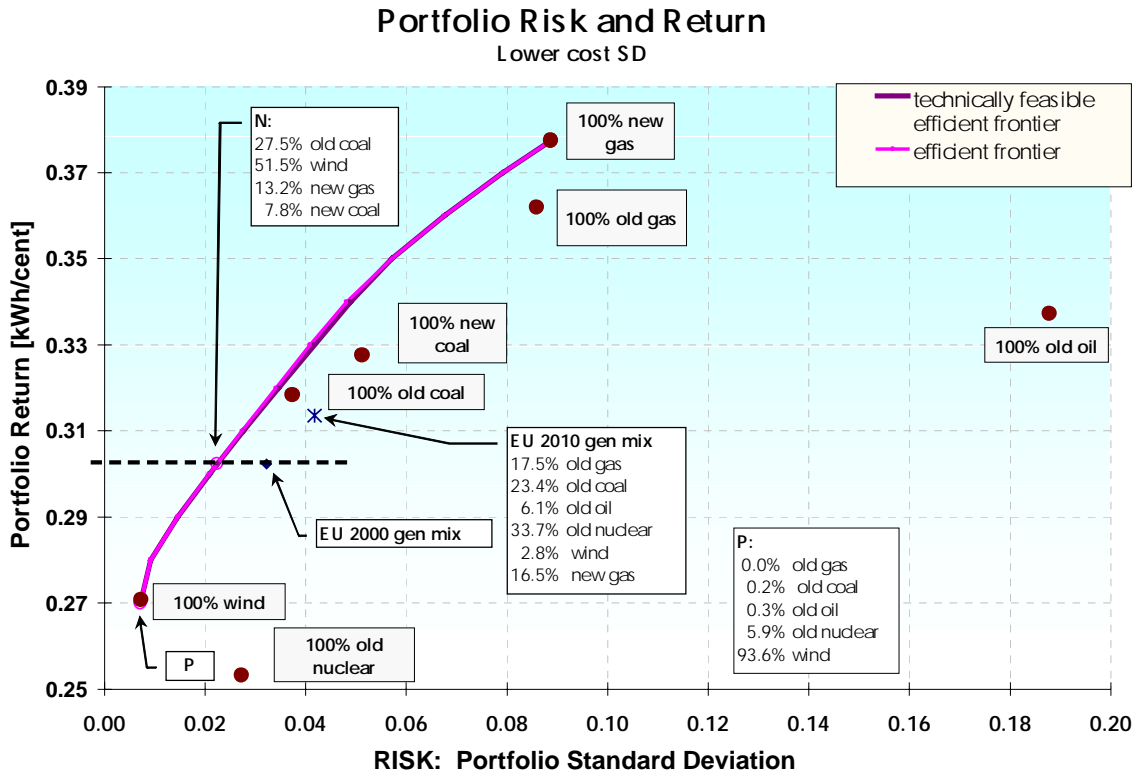


Figure 1B -1 Sensitivity analysis: the effect of lower cost SDs on the efficient frontier



**Figure 1B -2 Sensitivity analysis: the effect of lower cost SDs on the efficient frontier and the technically efficient frontier**

Figure 1B -2 shows that, unlike the base case results, (Section 3.4), the new efficient frontier (EF) is almost identical to the new FEF (*feasible efficient frontier*). The maximum deviation between the two frontiers occurs at a return of 0.33 kWh/cent where the risk of the new FEF is 0.042 as compared to 0.041 for the new EF (Table 1B-2).

Table 1B-2 also shows that the relative differences between the base-case FEF and new FEF as well as the new and base-case efficient frontiers are all quite similar.

**Table 1B-2 Efficient frontiers – sensitivity analysis on different SD of cost streams**

Return level [kWh/cent]	Efficient Frontier (EF)			Feasible Efficient Frontier (FEF)		
	Base Case Risk	New Risk	Risk difference	Base Case Risk	New Risk	Risk difference
0.2700		0.0071			0.0071	
0.2800	0.0189	0.0092	-51.5%	0.0189	0.0092	-51.5%
0.2900	0.0217	0.0145	-33.2%	0.0217	0.0145	-33.2%
0.3000	0.0263	0.0208	-20.9%	0.0268	0.0208	-22.3%
0.3100	0.0323	0.0273	-15.3%	0.0334	0.0276	-17.5%
0.3200	0.0385	0.0340	-11.5%	0.0412	0.0346	-16.0%
0.3300	0.0453	0.0408	-10.0%	0.0495	0.0417	-15.7%
0.3400	0.0535	0.0480	-10.3%	0.0581	0.0489	-15.9%
0.3500	0.0643	0.0572	-11.2%	0.0670	0.0572	-14.7%
0.3600	0.0767	0.0676	-12.0%	0.0767	0.0676	-12.0%
0.3700	0.0900	0.0791	-12.1%	0.0900	0.0791	-12.2%

**Content of Base Case EF vs. New EF**

The content of the new efficient frontier is shown in Figure 1B-3, which indicates some changes in the efficient mixes compared to the base case EF (Figure 1-16). First, wind now has a larger share—especially at lower return levels— e.g. at 0.27 kWh/cent the wind share is over 90% as compared to 58% in the base case. This higher share for wind comes at the expense of nuclear, “old coal” and “old gas”. Second, the efficient mixes do not include “old gas” and instead show “new coal”, especially at the higher return levels<sup>100</sup> Third, the fraction of “new gas” has increased compared to the base case. At 0.37 kWh/cent, for instance, the share has grown from 74% to 85%.

**Content of New EF vs. New FEF**

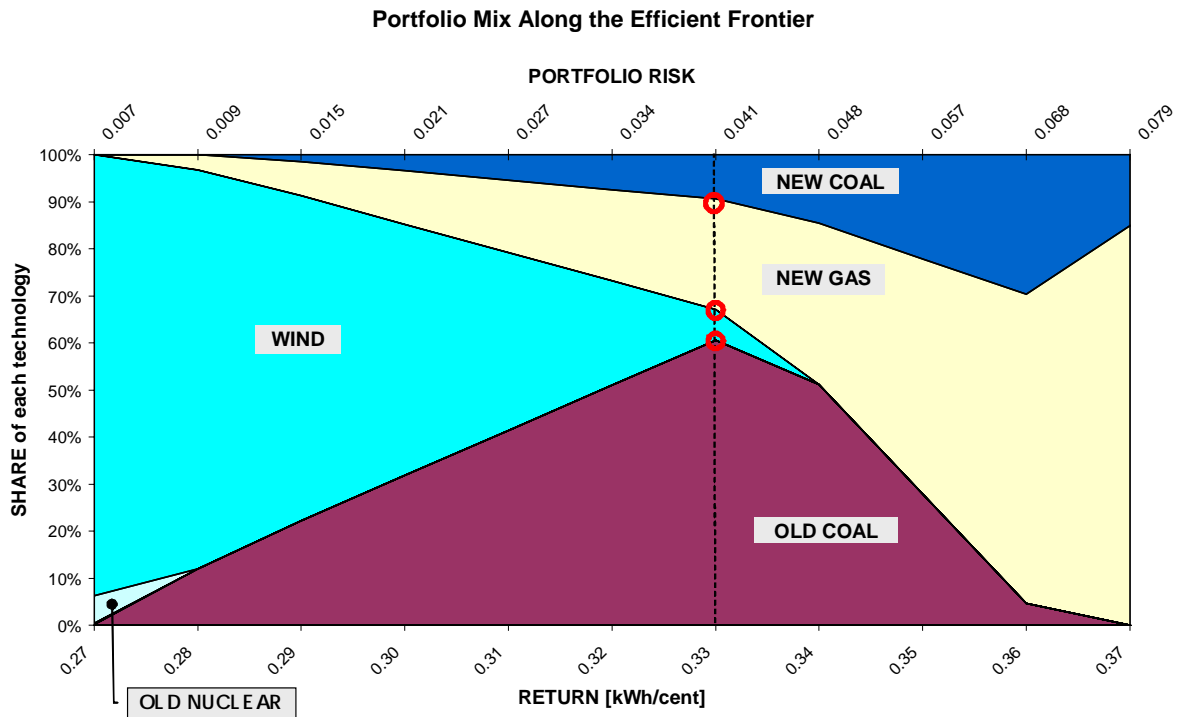
Figure 1B-3 and Figure 1B-4 enable us to compare the technology makeup of the new EF (Figure 1B-3) relative to the new FEF (Figure 1B-4). The principal difference is that the share of “old coal” in the FEF is limited to approximately 27.5%, a share that corresponds to the actual generation of coal in the EU mix. Where the fraction of coal in Figure 1B-3 exceeds this limit, mainly “new coal” replaces “old coal” in the new FEF (Figure 1B-3 – see e.g. for the return level of 0.33 kWh/cent in the two graphs).

**Content of Base Case FEF vs. New FEF**

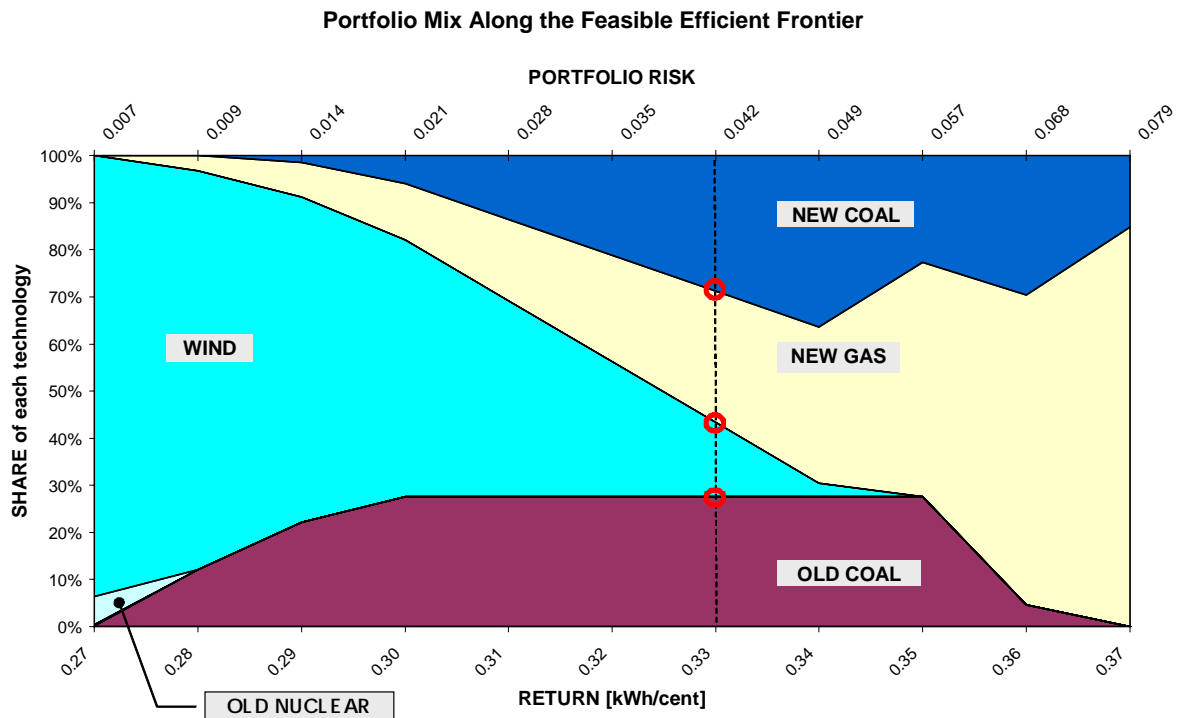
The differences between the content of the base case FEF (Figure 1-18) and the new FEF (Figure 1B-4) are the following. First, the share of wind at lower return levels is significantly higher in the new

<sup>100</sup> The reason why “old gas” is no longer included in the efficient frontier is that decommissioning costs are not considered so that the model can costlessly shift from old gas to the lower cost new gas. The inclusion of retirement costs in future analysis will help evaluate the extent to which this substitution of new for old gas is economically warranted (see Annex A).

FEF. This reduces the fraction of nuclear and “old coal” in the mix. Second, “old gas” is not included in the new frontier. Third, the share of “new coal” is significantly higher than in the old frontier, i.e. ranging up to 36% versus 6% before.



**Figure 1B-3** Sensitivity analysis of the portfolio mix along the efficient frontier using lower SD of cost streams



**Figure 1B-4:** Sensitivity analysis of the portfolio mix along the technically feasible frontier using lower SD of cost streams

The following conclusions about the sensitivity analysis on the standard deviations of cost streams can be drawn. First, the efficient mixes become less risky with the new (lower) standard deviations. Second, the share of wind is significantly increased when the variation of the cost streams is decreased. This is at the expense of “old coal” and nuclear. Third, the new efficient frontiers do not contain “old gas” but instead include larger fractions of new coal. Fourth, the EU-2000 mix is – once again – found to be inefficient and can be improved by including larger shares of wind. The same holds for the EU-2010 mix.

## B.2 Sensitivity analysis of the correlation coefficients

The results of the previous section suggest that reducing the estimated variability for the three non-fuel cost streams alter the efficient solutions by increasing the share of wind in the EF and FEF significantly.

With these variabilities set back to their base case levels, we now evaluate how changes (i.e. reductions) in correlation coefficients affect the efficient frontier. The correlation coefficients between technologies, for the three non-fuel cost streams were reduced from their original value of 0.7 to 0.1. Table 1B-3 shows the base case values from Table 1-7, (shown in parentheses) as well as the sensitivity values. The remaining coefficients were left unchanged.

**Table 1B-3 Base and alternate case correlations coefficients (Base case values in parentheses)**

Technology A	Technology B				
	Cost Category	Construction Period	Fuel	Variable O&M	Fixed O&M
Construction Period		(0.7) / <b>0.1</b>	(0) / 0	(0.1) / 0.1	(0.1) / 0.1
Fuel		(0) / 0	Table 1-8 <sup>101</sup>	(0) / 0	(0) / 0
Variable O&M		(0.1) / 0.1	(0) / 0	(0.7) / <b>0.1</b>	(0.1) / 0.1
Fixed O&M		(0.1) / 0.1	(0) / 0	(0.1) / 0.1	(0.7) / <b>0.1</b>

The sensitivity results suggest that significantly reducing the principal correlation-coefficients has a relatively small effect on the shape of the base case efficient frontier (Figure 1-15)- the divergence is not large enough to show graphically. The difference between the base case and the alternate case frontiers is a maximum of approximately 13% at lower return levels. It decreases as the portfolio returns rise. Table 1B-4 gives the risk for various return levels, starting with *P* – the lowest possible return of the efficient frontiers.

<sup>101</sup> This correlation is calculated on the basis of historical fuel prices.

**Table 1B-4 Sensitivity results: the effect of reduced correlations on the efficient frontier**

Return Level [kWh/cent]	Base Case Risk (SD)	Alternate Case Risk	Risk difference
0.2750	0.0184	0.0161	-12.7%
0.2800	0.0189	0.0167	-11.6%
0.2900	0.0217	0.0200	-7.8%
0.3000	0.0263	0.0251	-4.7%
0.3100	0.0323	0.0310	-4.0%
0.3200	0.0385	0.0377	-2.1%
0.3300	0.0453	0.0448	-1.3%
0.3400	0.0535	0.0529	-1.2%
0.3500	0.0643	0.0637	-1.0%
0.3600	0.0767	0.0762	-0.7%
0.3700	0.0900	0.0896	-0.5%

While the shape of the efficient frontier changes little throughout its range, its makeup is altered in the sense that “new coal” now becomes part of the efficient portfolio set at return levels exceeding 0.33 kWh/US cent. As compared to the base case (Figure 1-16) “old coal” is diminished and replaced by “new coal” in the mix. The highest fraction of “new coal”, 9.3%, is obtained at 0.37 kWh/cent.

To summarise, the base case portfolio proves to be very stable in response to a significant decrease in the correlation coefficients to 0.1. This does not alter the principal conclusions drawn from the base case discussion. Since the efficient frontier is not altered significantly, we did not estimate a revised FEF.

### **B.3 Sensitivity analysis of the cost streams**

In financial portfolios, equity share prices represent the risk-adjusted present value of all future cash flows.<sup>102</sup> Consistent with this, the efficient frontier is now estimated using risk-adjusted technology costs.

Table 1B-5 gives the calculated costs, which are developed here using the risk-adjusted procedures described in Section 2 of this document<sup>103</sup>.

<sup>102</sup> For details see e.g. Brealey and Myers (1991) p. 13-14.

<sup>103</sup> The estimates here do not exactly equal those shown in Section 2: the latter include the effect of taxes.

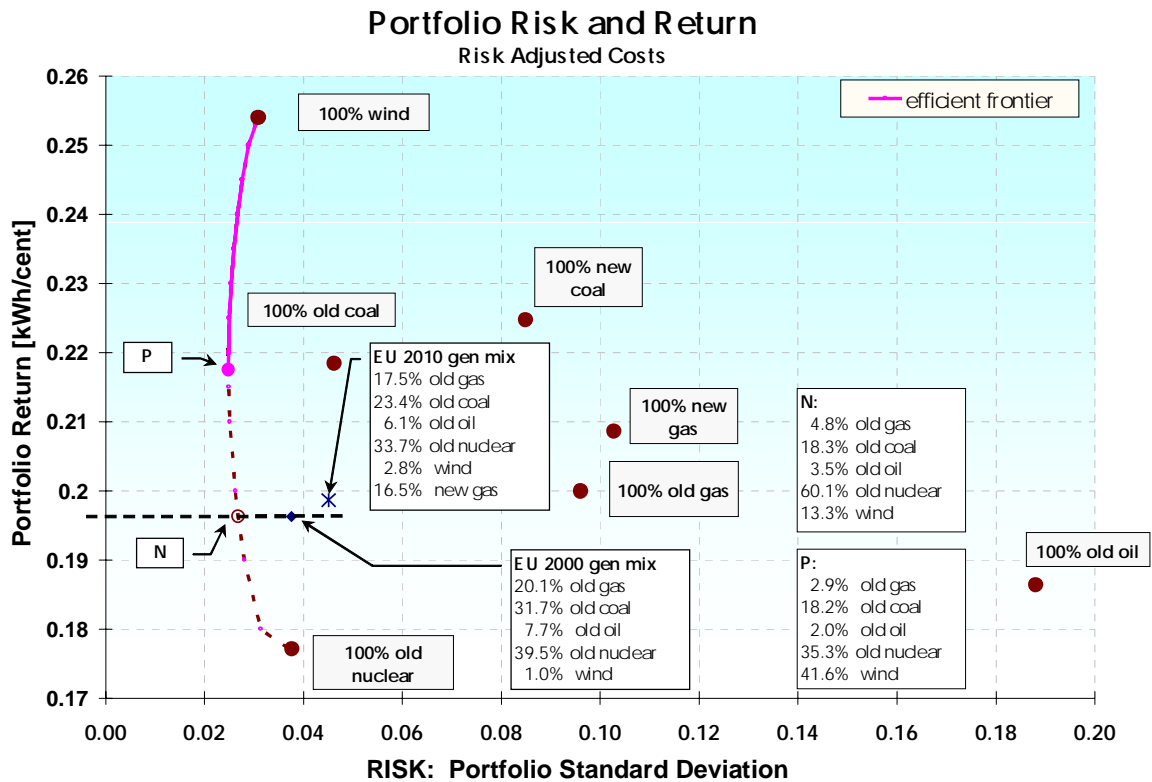
Table 1B-5 Risk adjusted costs<sup>104</sup>

ANNUAL COST US cents / kWh	GAS		COAL		OIL	NUCLEAR	WIND	
	CCGT	New Gas	Steam boiler	New Coal			Existing	New
Fixed investment	0.81	0.77	1.43	1.39	1.07	2.60	2.73	2.54
Fuel	3.66	3.51	2.22	2.16	3.76	1.71	0.00	0.00
Variable O&M	0.19	0.19	0.38	0.37	0.27	0.05	0.00	0.00
Fixed O&M	0.34	0.33	0.55	0.53	0.27	1.29	1.51	1.40
<b>Total busbar cost</b>	<b>5.00</b>	<b>4.79</b>	<b>4.58</b>	<b>4.45</b>	<b>5.37</b>	<b>5.65</b>	<b>4.24</b>	<b>3.94</b>
<b>Return (kWh/US cents)</b>	<b>0.200</b>	<b>0.209</b>	<b>0.218</b>	<b>0.225</b>	<b>0.186</b>	<b>0.177</b>	<b>0.236</b>	<b>0.254</b>

The resulting efficient frontier (Figure 1B-5) has a significantly different shape than the base case Figure 1-15. It covers different return levels than the base case, i.e. it ranges from 0.218 to 0.254 kWh/US cent, and is much steeper than the base case frontier. The EU-2000 and EU-2010 mixes are situated far to the right of the efficient frontier. In addition, there is no efficient mix with a return as low as the returns of EU 2000 and 2010.

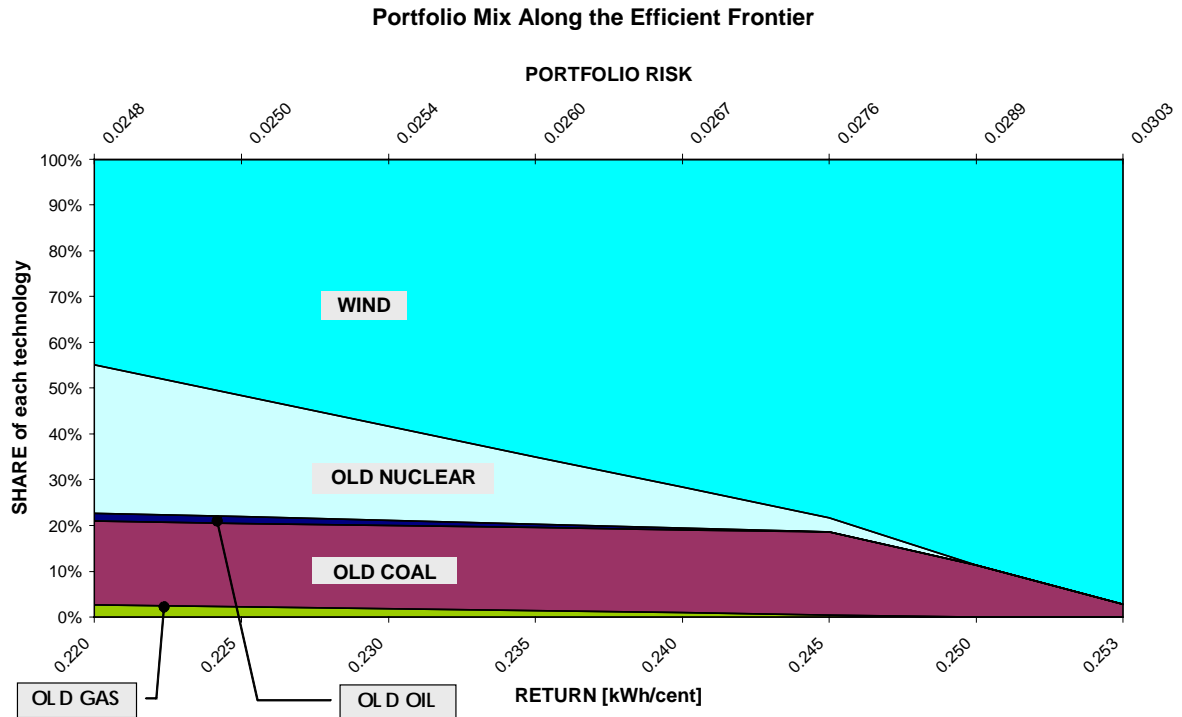
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<sup>104</sup> Based on Awerbuch (2002)



**Figure 1B-5 Sensitivity analysis: The effect of risk-adjusted costs on efficient portfolios**

The efficient frontier (Figure 1B-6) now includes substantial shares of wind, ranging from 42% to 100%. At the lower return levels, it contains some 35% nuclear. The higher the return, the more nuclear is replaced by wind. The fraction of old coal remains almost constant at 18% over the entire efficient frontier. The shares of oil and “old gas” do not exceed 3%. The EF does not include any new gas or new coal.



**Figure 1B-6 Sensitivity analysis of the portfolio mix along the efficient frontier using risk-adjusted costs**

The recommendation based on this analysis is to move from EU-2000 to at least portfolio *P* because it is the efficient mix that comes closest to it- although with higher return. *P* contains approximately 42% wind, 35% nuclear and 18% “old coal”.

To sum up, using risk-adjusted costs has a major impact on the efficient frontier. It decreases the return of *P*- the lowest possible return of the efficient frontier- from 0.275 kWh/cent to 0.218 kWh/cent (and also of EU-2000 and EU-2010). The highest portfolio return attainable is 0.254 kWh/cent.

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