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Versorgungssicherheit und Diversifizierung der Energieversorgung in der EU

Mean-Variance Portofolioanalyse des Stromerzeugungsmix und Auswirkungen auf die Bedeutung erneuerbarere Energieträger

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Martin Berger, Shimon Awerbuch, Reinhard Haas

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Vorwort

Diese Arbeit wurde im Rahmen einer "in-kind contribution" an der Internationalen Energieagentur (International Energy Agency - kurz IEA) in Paris durchgeführt. Der dafür nötige 6-monatige Aufenthalt von Martin BERGER an der IEA wurde vom Bundesministerium für Verkehr, Innovation und Technologie finanziert. Die Arbeit erfolgte in enger Zusammenarbeit mit Dr. Shimon Awerbuch, der an der IEA in der "Renewable Energy Unit" als Senior Advisor tätig ist.

Die Autoren möchten an dieser Stelle sowohl dem Bundesministerium für Verkehr, Innovation und Technologie als auch der IEA danken, die durch ihre Kooperation die Durchführung eines - unser Meinung nach - sehr interessanten Forschungsprojekts ermöglicht haben.

Kurzfassung

In Europa und in den USA haben Entscheidungsträger der Energiepolitik quantitative Ziele für die Stromproduktion aus Erneuerbaren festgesetzt oder sind dabei, diese Maßnahme zu erwägen. Das erfolgt meistens in der Auffassung *etwas* tun zu müssen, um eine gewisse Unabhängigkeit von fossilen Brennstoffen zu erreichen bzw. sich in Richtung der in Kyoto festgelegten Ziele zu bewegen. Hintergrund dieser Maßnahme ist die weit verbreitete Annahme, dass mit Erreichung dieser Ziele auch eine Erhöhung der durchschnittlichen Stromerzeugungskosten einhergeht. Erneuerbare scheinen für sich alleine betrachtet mehr zu kosten.

Es kann jedoch mit Hilfe der Standard Mittelwert-Varianz-Portfolioanalyse (*mean-variance portfolio analysis*) in dieser Arbeit gezeigt werden, dass - unter den im Anhang angeführten Bedingungen - eine Einbeziehung von Fixkosten-Technologien in ein konventionelles Stromportfolio dazu dienen kann, die durchschnittlichen Stromerzeugungskosten UND das Risiko zu senken.

Im Detail analysiert dieser Bericht den EU Strommix für das Jahr 2000 und projektierte Mixe für 2010. Es werden deren Portfoliorisiko und -ertrag mit einer Reihe von optimalen (d.h. effizienten) Portfolios verglichen, die sowohl minimale Erzeugungskosten bei gegebenem Marktrisiko, als auch minimales Risiko bei gegebenem Ertrag aufweisen. Im Allgemeinen deuten die Ergebnisse darauf hin, dass der EU-2000 und auch die projektierten EU-2010 Erzeugungsmixe, aus der Perspektive des Portfoliorisikos und -ertrags sub-optimal sind. Die Analyse ergibt, dass Portfolios mit geringeren Erzeugungskosten und geringerem Risiko einerseits durch Einbeziehung von größeren Anteilen an Erneuerbaren, die nur Fixkosten aufweisen, gebildet werden können. Andererseits kann dies auch durch Anpassung des konventionellen Stromportfolios geschehen.

Abstract

In Europe and the US policy makers are considering or have already implemented renewables targets or portfolio standards, in the general motivation that they need to do *something* in order to assure Kyoto compliance and a certain amount of independence from fossil fuels. Underlying these targets is the widespread belief that their adoption will increase overall generation costs since renewables seem to "cost more" on a stand alone basis. However, using standard "mean-variance" portfolio theory, it can be shown, that - under the conditions specified - adding fixed-cost generating technologies to a conventional generating portfolio serves to *lower* overall generating cost and risk.

This paper analyses existing and projected EU generating mixes and compares their risk-return properties to a set of optimal (i.e. efficient) portfolios that minimise generation cost at any given level of market risk, while minimising risk at any given overall generating cost level. In general, the results indicate that the existing and projected EU generating mixes are sub-optimal from a risk-return perspective. The analysis further suggests that portfolios with lower cost and risk can be developed by including greater amounts of fixed-cost renewables and by adjusting the conventional mix.

Content

0. Zusammenfassung

0.1. Einleitung

Portfoliotheorie ist ein Teil der Finanztheorie und ist heute bei Investoren weit verbreitet. Sie wird verwendet, um stabile Portfolios zu kreieren, die effiziente Ergebnisse unter verschiedensten ökonomischen Bedingungen sichern. *Effiziente Portfolios* sind dadurch charakterisiert, dass sie entweder einen maximalen Ertrag bei gegebenem Risiko aufweisen, oder minimales Risiko bei gegebenem Ertrag.

Wie im *Green Paper on security of supply* der EU[1] erwähnt, stellt die Abhängigkeit der EU von fossilen Brennstoffimporten[2] ein bedeutendes Risiko für die Gemeinschaft dar. Deshalb wird darin vorgeschlagen, die Abhängigkeit von Brennstoffimporten durch sowohl Produktdiversifikation als auch durch räumliche Diversifikation zu senken.

Im Fall von Energieportfolios können Portfoliotechniken der Energiepolitik den Weg in Richtung eines effizienten diversifizierten Portfolios zeigen, das bei bekanntem Risiko entsprechende (erwartete) Erzeugungskosten aufweist. Energiesicherheit wird dann reduziert, wenn Länder (aber auch Firmen) ineffiziente Energieportfolios halten, die unnötigem Kostenrisiko ausgesetzt sind.

Mehr und mehr Studien belegen, dass fossile Preisschwankungen die Wirtschaft eines Landes, das fossile Brennstoffe importiert, negativ beeinflussen. Schon einige Prozent Preisanstieg können zu deutlichen ökonomischen Verlusten durch Arbeitslosigkeit, zu Einkommensverlusten und auch zu Verlusten bei Finanzkapital führen. [3]

Traditionelle Energieplanung versucht eine *least-cost* Alternative auf Basis der Kosten einer einzelnen Technologie zu finden: Es ist allerdings in dem heutigen - durch die fortschreitende Liberalisierung der Energiemärkte - dynamischen Umfeld wahrscheinlich unmöglich, die für 30 Jahre gültige optimale Variante auf diese Art und Weise zu ermitteln. Die moderne Portfoliotheorie hat für die Energieplanung ein besseres Werkzeug zu bieten.

Wie im finanziellen Bereich ist es auch bei der Elektrizitätserzeugung wichtig, den Erzeugungsmix nicht aufgrund von heutigen Kosten jeder einzelnen Technologie zu ermitteln,

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[1] Green Paper "Towards a European strategy for the security of energy supply" [European Community 2001]

[2] The EU is aware of the risks that are linked to its dependence on imported fuels and aims to lower them in order to be able to provide *"...uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development..."*. Being conscious of the weaknesses of fossil fuels the commission furthermore states that "*among the objectives to be pursued are those balancing between and diversifying the various sources of supply (by product and by geographical region).*"

[3] Diese Verluste können in die 10.000 und sogar 100.000 Mrd. US$ gehen [Sauter und Awerbuch 2002]. Ein exzellenter Überblick über die aktuelle Literatur zu diesem Thema kann auch in Papapetrou (2001) gefunden werden; siehe auch Sadorsky (1999), Yang, et al. (2002) und Ferderer (1996).

sondern auf Basis der erwarteten Kosten eines Energieportfolios. Zu jedem Zeitpunkt wird eine bestimmte Technologie in dem Portfolio hohe Kosten aufweisen, während andere niedrige Kosten besitzen. Über die Zeit gesehen allerdings führt die geschickte Kombination dieser Technologien zu minimalen Gesamt - Portfoliokosten bei gegebenem Risiko. Die bedeutende Folgerung aus Portfolio – basierter Analyse ist, dass der relative „Wert" von Technologien nicht durch Untersuchung von alternativen Technologien ermittelt werden darf, sondern durch Bewertung von alternativen Portfolios.

Die vorliegende Arbeit stellt ein erstes Vortasten in Richtung einer Portfolioanalyse des Stromerzeugungsmixes dar. Hierfür wird die klassische Mittelwert-Varianz (MV) Portfolioanalyse (*Mean-Variance Portfolio Analysis*) zur Ermittlung von effizienten Stromportfolios eingesetzt. Es werden dabei die Stromerzeugungskosten und ihre Risiken, d.h. historische Standardabweichung und Korrelationen bei Brennstoffpreisen, Betriebskosten und Baukosten untersucht. Die Analyse wird auf einen Mix aus konventionellen und erneuerbaren Technologien angewendet.[4] Finanzielle Instrumente zur Risikominderung werden hier nicht betrachtet.

Strommarktpreise weisen Preisfluktuationen auf, die durch Faktoren wie strategisches Verhalten einzelner Marktteilnehmer, Ausübung von Marktmacht und zufällige tägliche Ereignisse (Ausfälle von Erzeugungseinheiten, Wetter, etc.) bestimmt werden.[5] Diese Art der Volatilität wird in der folgenden Analyse allerdings nicht behandelt, denn eine Beschränkung der Anwendung der MV-Theorie auf Erzeugungskosten und deren Risiken schließt diese Seite des Risikos für Stromproduzenten und Händler aus.

Die für die Portfolioanalyse verwendeten Kosten basieren auf WEO (2000) und berücksichtigen keine Externalitäten. Auch Steuern und Subventionen sind nicht beinhaltet.

0.2. Die Portfoliotheorie

Die heute angewendete Portfoliotheorie basiert im Prinzip auf einer Publikation von Harry Markowitz (1952). Sie wurde ursprünglich nur im Zusammenhang mit Finanzportfolios eingesetzt. Die Grundidee ist, dass obwohl Investitionen für sich gesehen unsicher und riskant sind, es durch ihr zeitliches Zusammenwirken (*Kovarianz*) zur Verringerung des Gesamtrisikos bis theoretisch Null kommen kann.

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[4] Es wird in dieser Analyse davon ausgegangen, dass jede Technologie unabhängig von ihrer Art in ein Netz einspeisen kann, das keinen Engpässen bei der Einspeisung unterliegt. Der Ort der Einspeisung ist dabei ebenso egal wie die Menge und mögliche Schwankungen. Bezüglich weiterer Annahmen und Einschränkungen für die hier verwendete Analyse siehe Anhang (Appendix A);

[5] Teilweise können diese Faktoren durch die richtige Ausgestaltung der Rahmenbedingungen des Strommarktes beherrscht werden.

Die klassische MV Portfolioanalyse charakterisiert jedes Wertpapier durch seinen erwarteten Ertrag $E(r_i)$[6], seine Standardabweichung (SD, σ_i) und die Kovarianz (COV)[7] zu den anderen Wertpapieren. Die SD und COV werden im Allgemeinen mittels historischer Zeitreihen geschätzt. Eine wesentliche Voraussetzung für die Anwendung der MV Portfoliotheorie ist, dass entweder eine symmetrische Verteilung der Erträge vorliegt, oder eine quadratische Nutzenfunktion vorausgesetzt werden kann.[8] Da eine Normalverteilung die Anforderung der Symmetrie erfüllt, wird häufig angenommen, dass die Erträge standard-normalverteilt sind.

In diesem Fall ist der erwartete Ertrag eines Portfolios aus zwei Wertpapieren $E(r_p)$ das gewichtete Mittel der beiden erwarteten Erträge $E(r_1)$ und $E(r_2)$:

$$E(r_p) = X_1 \bullet E(r_1) + X_2 \bullet E(r_2) \qquad (0.1)$$

hier ist

X_1, X_2 der Anteil der zwei Wertpapiere am Portfolio; $\Sigma X_i = 1$;

Das MV Portfoliorisiko ist gegeben durch[9]

$$\sigma_p = \sqrt{X_1^2 \sigma_1^2 + X_2^2 \sigma_2^2 + 2 X_1 X_2 \rho_{12} \sigma_1 \sigma_2} \qquad (0.2)$$

Die *Korrelation* ρ_{12} kann Werte zwischen -1 und +1 annehmen.[10] Figure 0-1 zeigt ein typisches Ergebnis der MV Portfolioanalyse. Wertpapier *A* besitzt eine höhere SD und einen

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[6] Der Periodenertrag wird durch folgende Formel angegeben [Seitz (1990) p. 225]: $r_s = \frac{EV - BV + CF}{BV}$ hier sind *EV* der Endwert des Wertpapiers, *BV* der Startwert und *CF* die Einnahmen während der untersuchten Periode;

[7] Die Kovarianz von zwei Erträgen kann durch $COV_{12} = \rho_{12} \sigma_1 \sigma_2$ berechnet werden. Hier ist $\rho 12$ die Korrelation zwischen den Erträgen der beiden Wertpapiere.

[8] Quadratische Nutzenfunktionen sind deshalb eher unattraktiv, weil sie absolut ansteigende Risikoaversion implizieren. Anders ausgedrückt bedeutet das, dass Investoren mit dieser Nutzenfunktion umso höhere Risikoprämien für eine bestimmte Investition verlangen, je mehr ihr Reichtum sich vergrößert. Dieses Verhalten steht im Gegensatz zu Intuition und zu dem bei Investoren tatsächlich beobachteten Verhalten [Harlow 1991].

[9] Die Gleichung kann auch umgeschrieben werden zu $\sigma_p = \sqrt{X_1^2 \sigma_1^2 + X_2^2 \sigma_2^2 + 2 X_1 X_2 COV_{12}}$.

[10] Der Korrelationskoeffizient beschreibt das Ausmaß des linearen Zusammenhanges zwischen zwei Variablen. Eine perfekte Korrelation weist einen Korrelationskoeffizienten von +1 auf. Trägt man in diesem Fall jede der beiden Variablen auf einer Achse eines x-y Diagramms auf, dann fallen alle Punkte auf eine ansteigende Gerade. Nimmt man als Variablen die Preise von 2 Wertpapieren *A* und *B*, dann zeigt sich in diesem Fall folgender Zusammenhang: steigt der Preis von *A* an, dann tut es auch der von *B*. Im umgekehrten Fall, fällt der Preis von *A*, dann fällt auch der von *B*. Bei einem Korrelationskoeffizienten von -1 verhält sich *B* umgekehrt zu *A*, d.h. steigt der Preis von *A*, dann fällt der von *B*. Im erwähnten

höheren erwarteten Ertrag und *B* einen niedrigeren Ertrag und gleichzeitig auch ein niedrigeres Risiko. Es lassen sich nun je nach vorhandener Korrelation zwischen den beiden Wertpapieren unendlich viele Kombinationen der beiden bilden. Diese liegen auf den Kurven, die die Punkte *A* und *B* verbinden.

Aus der geschickten Kombination von zwei riskanten Wertpapieren mit einer Korrelation kleiner als 0,7 entsteht ein Mix, der ein Portfoliorisiko aufweist, das geringer ist, als das von jedem einzelnen der beiden. Mit ρ_{12} = -1 gibt es sogar einen Mix, wo das Portfoliorisiko bei einem bestimmten erwarteten Ertrag Null wird. Dieser Effekt wird *Portfolio Effekt* genannt und tritt durch *Diversifikation* auf.

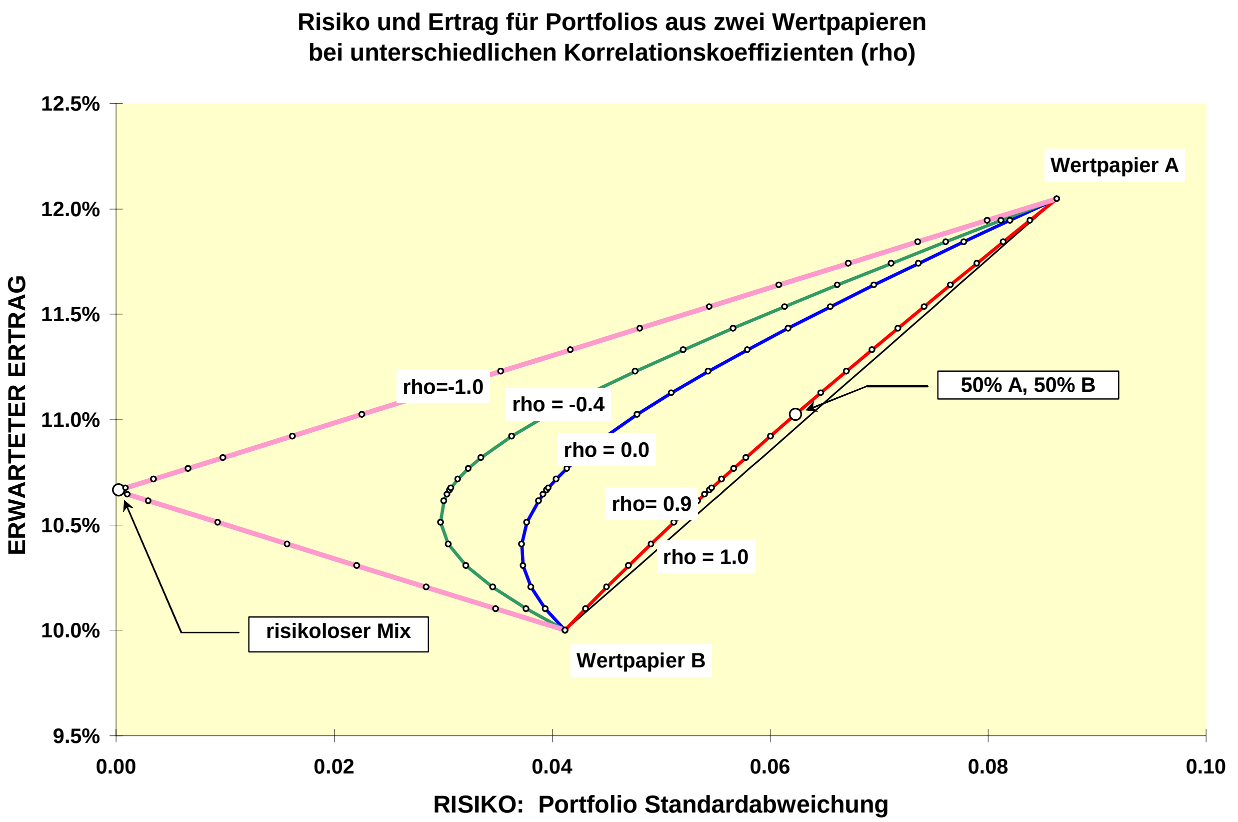

Figure 0-1 Risiko und Ertrag bei verschiedenen Korrelationskoeffizienten und der Portfolio Effekt

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Diagramm ergibt das eine fallende Gerade. Ist der Koeffizient gleich Null, dann heißt das, dass kein linearer Zusammenhang zwischen den beiden besteht. *Unkorreliert* bedeutet aber nicht *unabhängig*, denn ein nicht-linearer Zusammenhang ist nicht auszuschließen.

Was nun am Beispiel von zwei Wertpapieren gezeigt wurde, lässt sich theoretisch auf beliebig viele erweitern. Das Prinzip bleibt stets dasselbe:[11] der mit dem Anteil gewichtete erwartete Ertrag jedes einzelnen Wertpapiers addiert ergibt den erwarteten Ertrag des Portfoliomixes. Für die Berechnung des Risikos wird der Term mit dem Anteil des neuen Wertpapiers am Mix mit der Standardabweichung multipliziert, dann quadriert und schließlich zu dem Rest addiert. Außerdem werden entsprechende Terme addiert, die die Kovarianz des neuen Wertpapiers mit den übrigen Vermögenswerten beschreibt.

Wie in Figure 0-2 durch zahlreiche „x“ angedeutet, gibt es unendlich viele Kombination der in ein Portfolio aufgenommenen Wertpapiere, aber nur bestimmte liegen auf der stark gezeichneten Kurve, die bei gegebenem Ertrag, den Mix mit dem minimalen Risiko aufweist. Punkte wie *A* weisen zwar ebenfalls das minimale Risiko bei einem bestimmten Ertrag auf, werden aber von Punkten wie *C* dominiert, die bei gleichem Risiko einen höheren erwarteten Ertrag besitzen. Die sich ergebende Kurve wird Effiziente Grenze (*Efficient Frontier)* genannt. In dem abgebildeten Fall zieht sie sich von *B* über *C* nach *D*.

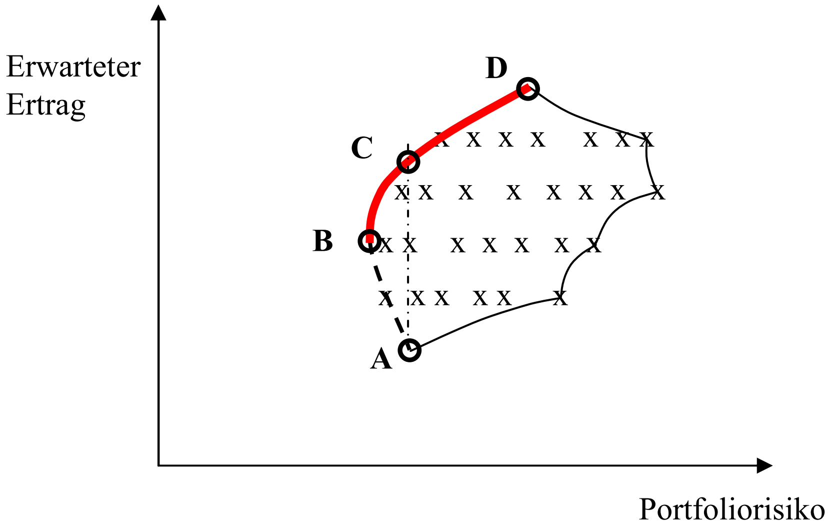

Figure 0-2 Die Effiziente Grenze (*Efficient Frontier*) eines Portfolios mit mehr als zwei Wertpapieren

Ein interessanter und sehr wichtiger Effekt ergibt sich, wenn zu dem Portfolio aus risikoreichen Wertpapieren ein risikoloses Wertpapier, z.B. eine Staatsanleihe, hinzugefügt wird. Auf dem Portfoliographen kommt dieser Vermögenswert daher irgendwo auf der y-Achse zu liegen, siehe Punkt r_f in Figure 0-3. Wie am Beispiel eines Zwei-Wertpapier-Portfolios mathematisch leicht gezeigt werden kann, vereinfacht die Einbeziehung eines risikolosen Wertpapiers die Effiziente Grenze (EG) zu einer Gerade, die auf der y-Achse mit

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[11] Im Fall von drei Wertpapieren wird die Formel zur Berechnung des Portfoliorisikos erweitert zu (siehe Gleichung 0.2)

$$\sigma_p = \sqrt{X_1{}^2\sigma_1{}^2 + X_2{}^2\sigma_2{}^2 + X_3{}^2\sigma_3{}^2 + 2X_1X_2\rho_{12}\sigma_1\sigma_2 + 2X_1X_3\rho_{13}\sigma_1\sigma_3 + 2X_2X_3\rho_{23}\sigma_2\sigma_3}\ .$$

Gleichung (0.1) wird zu $E(r_p) = X_1 \bullet E(r_1) + X_2 \bullet E(r_2) + X_3 \bullet E(r_3)$

r_f beginnt und die in Figure 0-2 abgebildete EG tangiert.[12] Der Tangentialpunkt *M* stellt den optimalen Mix aller riskanten Wertpapiere dar.[13]

Punkt *H* in Figure 0-3 zum Beispiel gibt den erwarteten Ertrag und das Risiko eines Portfolios aus 50% risikolosen und 50% riskanten Wertpapieren (genauer gesagt 50% von *M*). Portfolio *K* andererseits enthält ca. 40% risikolose und 60% riskante Wertpapiere. Dieser Mix weist denselben erwarteten Ertrag wie *B* auf, aber sein Risiko ist geringer.

Ein Investor kann also nun beliebig einen Punkt auf der Geraden r_f – M (der neuen EG) wählen, der zwischen 0% und 100% *M* bzw. 100% und 0% r_f enthält. Gegenüber dem Portfolio, das nur riskante Wertpapiere enthält, bietet also die Einbeziehung eines risikolosen Wertpapiers die wichtige Möglichkeit Risiko bei gleichem erwartetem Ertrag zu reduzieren.

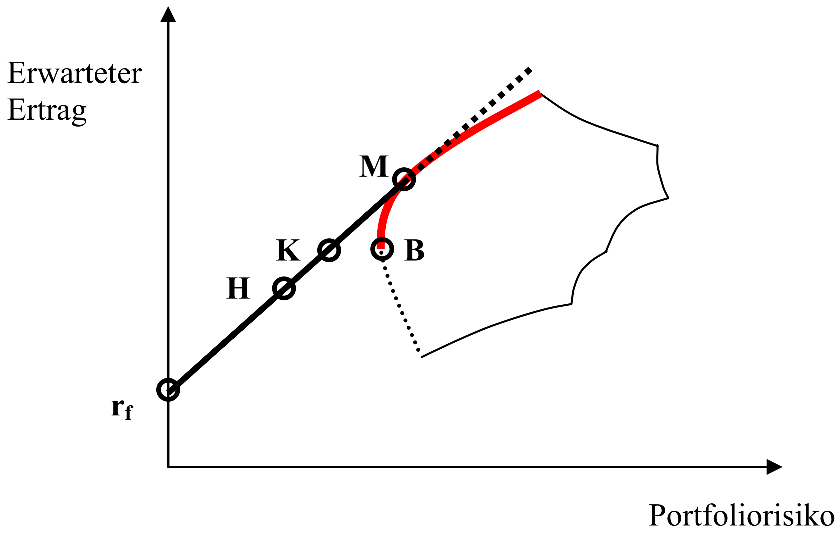

Figure 0-3 Portfolios mit riskanten und einem risikolosen Wertpapier

[12] Die Einbeziehung eines risikolosen Wertpapiers, dessen SD Null ist, vereinfacht die Formel (0.2) so, dass die effizienten Risiko-Ertrag-Kombinationen nun auf eine Gerade fallen. Wenn Wertpapier *1* risikolos ist, dann ist $\sigma_1 = 0$ und auch $COV_{12} = 0$, so dass das Portfoliorisiko σ_p durch folgende Formel angegeben werden kann: $\sigma_p = \sqrt{X_2^2 \sigma_2^2} = X_2 \sigma_2$. Dies entspricht einer Gerade.

[13] Der Tangentialpunkt *M* stellt den Punkt dar, der die *Portfolio Performance* θ

$$\theta = \frac{E(r_p) - r_f}{\sigma_p}$$

maximiert - siehe dazu auch Kwan (2001) p. 72.

0.3. Die Übertragung der Portfoliotheorie auf Erzeugungsportfolios

Die in dem vorangegangen Kapitel dargestellten Zusammenhänge können auf Erzeugungsportfolios oder sonstige „*Real Assets*" übertragen werden. In diesem Fall kann das Marktrisiko auf eine ähnliche Weise definiert werden, wie für Wertpapiere. Es wird mittels der Standardabweichung (SD) der Periodenerträge (HPR) der Kosten ermittelt, z.B. der Brennstoffkosten.[14] Der erwartete Ertrag einer Technologie wird hier als invertierte erwartete Kosten der Stromerzeugung interpretiert, d.h. die Einheit beträgt kWh/Cent.[15]

Die Übertragung der Portfoliotheorie von Wertpapieren auf Erzeugungsportfolios sollte nicht erfolgen, ohne sich vorher die Einhaltung von einigen Bedingungen anzusehen. Dazu gehören z.B. die Symmetrie der Verteilung der Erträge, die Existenz von perfekten Märkten, fungible Vermögenswerte, Teilbarkeit. Für Details dazu siehe Appendix A.

Obwohl die oben genannten Bedingungen nicht in allen Fällen erfüllt werden können, ist anzumerken, dass die Portfoliotheorie häufig bei greifbaren, nicht-finanziellen Vermögenswerten Anwendung findet [siehe z.B. Seitz (1990), Helfat (1988), Herbst (1990)].

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[14] Portfoliorisiko: Wie vorher angegeben, ergibt sich der Periodenertrag zu $r_s = \frac{EV - BV + CF}{BV}$ -- Im Fall von Risiko der Brennstoffkosten ist *CF* gleich Null, *EV* ist der Preis des Brennstoffes pro Einheit (kWh) in Periode *t* und *BV* der Preis in Periode *t-1*. Wenn statt der SD der Periodenerträge die SD der Brennstoffpreise direkt zur Ermittlung des Risikos herangezogen würde, dann bekäme man ein verzerrtes Ergebnis [Herbst (1990) p. 255]: Eine Technologie mit hohen Brennstoffpreisen könnte eine höhere SD aufweisen, als eine mit niedrigeren Preisen, einfach aufgrund der absoluten Höhe der Brennstoffpreise. Deshalb verwendet die Portfoliotheorie ein relatives Maß für die Abschätzung des Risikos, nämlich Periodenerträge.

[15] Portfolioertrag: Diese Analyse basiert im Gegensatz zu Finanzportfolios auf Kosten, weil aus Sicht der Gesellschaft Kosten (und Risiken) minimiert, anstatt finanzielle Erträge (in Prozent) maximiert werden. Würde man sie auf Einnahmen aus Stromverkäufen basieren lassen, dann wären die Risiken, die mit der Volatilität auf den Strommärkten verbunden sind, auch mit zu berücksichtigen.

Finanzielle Erträge werden im Allgemeinen als Bruch - Gewinne dividiert durch Input - dargestellt, d.h. € Gewinn/€ Input. Diese Maßzahl ist also dimensionslos. Das gilt nicht für die in dieser Publikation gewählte Ertragskennzahl [kWh/Cent]. Sie wird nur dann dimensionslos, wenn dem Zähler ein monetärer Wert zugeordnet wird.

Multipliziert man die hier gewählte Ertragskennzahl mit dem Strompreis [Cent/kWh], dann erhält man wieder eine dimensionslose Messgröße für den Ertrag. Dieses Vorgehen wirft jedoch die Frage nach dem richtigen zu wählenden Elektrizitätspreis auf.

Würden für die nachfolgende Analyse die Preise für täglich auf dem Spotmarkt zu kaufenden Strom gewählt, dann müsste diesem zusätzlichen Risiko (Strompreisschwankungen) Rechnung getragen werden. Eine andere Möglichkeit die gewählte dimensionslose Ertragsgröße zu erhalten, wäre im Zähler unserer Ertragskennzahl [kWh/Cent] die durchschnittlichen auf WEO (2000) basierten Kosten als Näherung für den Langzeit-Marktgleichgewichtspreis einzusetzen.

0.4. Analyse des EU Erzeugungsportfolios

Das entwickelte Modell zur Analyse des Erzeugungsportfolios der EU integriert vier konventionelle und eine erneuerbare Technologie. Die vier konventionellen sind Gas, Kohle, Öl und Nuklear. Die Technologie, die in dieser Analyse die Erneuerbaren repräsentiert, ist Wind.[16]

Das Risiko der erwähnten Technologien wird durch das Zusammenspiel der Risiken der folgenden vier Kostenkomponenten charakterisiert: i) Investitions- und Planungskosten, ii) Brennstoffkosten, iii) variable Betriebs- und Wartungskosten (O&M) und iv) fixe O&M. Table 0-1 gibt einen Überblick über die verwendeten Kosten für die verschiedenen Technologien. Die invertierten kWh-Kosten der einzelnen Technologien geben die jeweiligen „Erträge" in [kWh/Cent].

Die hier verwendeten Kosten stammen von WEO (2000). Im Anhang ist eine Sensitivitätsanalyse dokumentiert, bei der das Modell - unter anderem - mit unterschiedlichen Kosten getestet wird. Dabei finden sowohl ein Set von Risiko-korrigierten Kosten - basierend auf Awerbuch (2002) - als auch Kosten für die Windstromerzeugung aus dem EU-Projekt ElGREEN [Huber et al. 2001] Anwendung. Details dazu sind in Appendix B.3 und Appendix B.4 zu finden.

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[16] Diese „Erneuerbare Technologie" könnte man sich genauso als „Korb" von unterschiedlichen passiven Erneuerbaren (d.h. Technologien, die Strom erzeugen ohne einen Brennstoff zu verbrauchen) vorstellen, der aus z.B. Wind, Photovoltaik (PV), Wasserkraft, Geothermie, Gezeiten- und Solarkraftwerken besteht. Ein zusätzlicher Korb könnte dann aus Erneuerbaren bestehen, die Brennstoffkosten aufweisen, wie Biomasse, Biogas, etc. Wir beschränken uns in dieser Analyse allerdings auf Wind als Repräsentant der passiven Erneuerbaren, weil diese Technologie relativ große Akzeptanz erfährt und große Wachstumsraten hat. Außerdem ist sie durch kurze Vorlaufzeiten gekennzeichnet, modular und flexibel.

Table 0-1 Jährliche Kosten der untersuchten Technologien [WEO 2000][17]

JÄHRLICHE KOSTEN in Cent / kWh	GAS		KOHLE		ÖL[18]	NUKLEAR	WIND	
	Existierende GuD	Neu	Existierende Dampfkessel	Neu			Existierend	Neu
Investition und Planung	0.64	0.59	1.24	1.18	0.59	2.26	3.08	2.80
Brennstoffe	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
Fixe O&M	0.18	0.18	0.28	0.28	0.15	0.66	0.89	0.89
Gesamtkosten	**2.76**	**2.65**	**3.14**	**3.05**	**2.96**	**3.95**	**3.97**	**3.69**
Ertrag (kWh/Cent)	**0.362**	**0.378**	**0.318**	**0.328**	**0.337**	**0.253**	**0.252**	**0.271**

Bei Gas, Kohle und Wind wird zwischen neuen, in der Zukunft zu errichtenden, und existierenden Anlagen unterschieden.[19] Der Unterschied bezüglich der Kosten liegt vor allem darin, dass die neuen Technologien durch Lerneffekte bedingte niedrigere Investitionskosten aufweisen. Außerdem sind die jährlichen Kosten für Brennstoffe durch erwartete Steigerungen des Jahresnutzungsgrades niedriger als im Jahr 2000.[20]

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[17] Hinter diesen jährlichen Kosten stehen z.B. im Fall von existierenden GuD - Anlagen Kapitalkosten von 650 €/kW, fixe Betriebs- und Wartungskosten von 15 €/kW/a, variable Betriebs- und Wartungskosten von 0,15 Cent/kWh, Brennstoffkosten von 110 €/toe, eine Vorlaufzeit von 3 Jahren, eine Lebensdauer von 30a, Zinssatz von 7%, Jahresnutzungsgrad von 52% und ein Kapazitätsfaktor von 85%. Für Anlagen im Jahr 2010 nimmt WEO (2000) nur Investitionskosten von 550 EU/kW an und erhöht den Jahresnutzungsgrad auf 56%. Die restlichen Parameter bleiben gleich. Beide, GuD im Jahr 2000 und GuD im Jahr 2010, werden auf jährliche Kosten umgerechnet. GuD 2000 entspricht den Werten in der Tabelle. Für die zukünftigen jährlichen Kosten einer Technologie ("NEU") wird der Mittelwert der jährlichen Kosten von GuD 2000 und GuD 2010 herangezogen.

[18] Eigene Berechnungen

[19] Ein wachsender Strombedarf wird im Allgemeinen durch den Bau von neuen Kapazitäten gedeckt. Erzeugter Strom hängt vom Einsatz der verfügbaren Kapazitäten ab, d.h. von ihren Volllaststunden. Das hier vorgestellte Modell arbeitet allerdings nicht mit installierten Kapazitäten sondern mit erzeugtem Strom. Es unterstellt daher durchschnittliche Volllaststunden für verschiedene Technologien.

[20] Das Potential von guten Windstandorten wird als ausreichend groß angenommen, so dass es 2005 in Europa zu keinen Steigerungen bei den Stromgestehungskosten – bedingt durch niedrigere Volllaststundenzahlen - im Vergleich zum derzeitigen Stand kommt.

Im Fall von Nuklearstromerzeugung wird davon ausgegangen, dass in der nahen Zukunft in Europa keine nennenswerten Kapazitäten mehr konstruiert werden (eine Ausnahme stellt Finnland dar). Auch ein Neubau von Kraftwerken, die (alleine) mit Öl befeuert sind, wird ausgeschlossen.

Betrachtet man ein Portfolios aus neuen und alten Anlagen so ist - abgesehen von unterschiedlichen Kosten zwischen alt und neu - eine neu zu installierende Anlage dadurch gekennzeichnet, dass sie neben den Risiken bedingt durch Betriebs- und Brennstoffkosten auch Investitions- und Planungskostenrisiko aufweist. Im Fall von bereits installierten Anlagen fallen die letzten beiden Komponenten weg.[21]

Die einzig interessanten Portfolios für die Energieplanung sind jene, die auf der Effizienten Grenze (EG) liegen, denn alle anderen liegen rechts davon und sind bei gegebenem Ertrag risikoreicher. Die EG lässt sich analytisch mithilfe der *Lagrange-Methode* berechnen, im vorliegenden Fall wurde sie jedoch mit Hilfe des EXCEL SOLVERs™ stückchenweise (diskret) ermittelt. Zu jedem gewählten diskreten Ertrag ergibt sich damit das Portfolio mit dem geringsten Risiko. Das Ergebnis ist eine EG, die vom Aussehen der von Figure 0-2 entspricht.

Würde man eine komplett risikolose Technologie einführen, d.h. weder Investitions-, Brennstoff-, noch Betriebs- oder Wartungsrisiko - denkbar wäre z.B. „Energiesparen“ -, dann erhielte man eine EG nach Figure 0-3 (r_f – M). Allerdings sind bereits erneuerbare Technologien wie Wind oder PV relativ risikolos: Sie weisen häufig ein - im Vergleich zu fossilen Anlagen - niedriges Investitionsrisiko auf, da sie oft modular und flexibel sind [Brower et al (1997), Hoff (1997) und Venetsanos et al. (2002)]. Außerdem gibt es kein Brennstoffrisiko, da ihr „Brennstoff“ keine direkten Kosten bedingt.[22]

Würde man zur Portfolioanalyse nur das Risiko, das durch die Brennstoffkosten erwächst, betrachten, dann wäre jede passive Technologie tatsächlich komplett risikolos. Diese

[21] Investitions- und Planungskosten werden - obwohl sie bereits zu den *sunk costs* zählen - bei Berechnung der Stromerzeugungskosten von bereits existierenden Anlagen natürlich berücksichtigt. Sie werden mit dem Annuitätenfaktor auf jährliche Kosten umgerechnet und ergeben addiert zu den anderen Kostenkomponenten die Gesamtkosten.

[22] Wie im Anhang (Appendix A) erläutert, gibt es bei passiven Technologien (d.h. Technologien, die Strom erzeugen ohne einen Brennstoff zu verbrauchen) wie Wind indirekte Kosten, sogenannte *Opportunitätskosten*. Sie ergeben sich aus der Volatilität des Windes. Bläst kein Wind, dann muß der Strom von einer anderen Technologie, einer *Backup-Technologie*, geliefert werden. Diese für den Energieversorger zusätzlich erwachsenden Kosten sind mit einem Kostenrisiko verbunden. Ist das Backup-System z.B. eine fossile Technologie, dann hat man theoretisch auch das damit verbundene Brennstoffrisiko zu berücksichtigen. In dieser Studie gehen wir aber vom vereinfachten Fall aus, dass keine zusätzliche Backup-Kapazität für neu installierte Windanlagen notwendig ist und vernachlässigen das Risiko von Opportunitätskosten. Nimmt man an, dass das Stromnetz der EU nur ein einziges Netz wäre (Details dazu Appendix A) und gegeben die Tatsache, dass das *Mid-term* Potential für 2010 [Huber et al. 2001] rund 7,9% der Stromerzeugung von 2010 beträgt, dann ist diese Annahme nicht unrealistisch: es existieren verschiedene Studien, in denen davon ausgegangen wird, dass ein Anteil von 5% bis 10% an Windstrom im Stromnetz nur geringe oder keine Änderungen in der Betriebsstrategie zu Folge haben [Wind Energy Weekly (1996), ERU (1995)].

vereinfachende Betrachtung ist deshalb interessant, weil Brennstoffe bei den fossilen Technologien (Gas, Kohle, Erdöl) einen Großteil der Kosten ausmachen (siehe Table 0-1).

0.4.1. Das Subportfolio

Jede Technologie ist durch ihre Standardabweichung (SD) der Periodenerträge der Kosten, die Korrelationen zu den anderen Technologien und ihrem erwarteten Ertrag [kWh/Cent] gekennzeichnet. Die SD und die Korrelationen einer Technologie ergeben sich aus einem Sub-Portfolio bestehend aus den vier Kostenkomponenten - z.B. bei existierenden Gaskraftwerken ergibt sich das Subportfolio zur Risikoberechnung aus 23,3% Investitionsrisiko, 65,7% Brennstoffrisiko, 4,6% variablem O&M-Risiko und 6,4% fixem O&M-Risiko. Diese Prozentwerte berechnen sich aus den Anteilen der Kostenkomponenten an den jeweiligen Gesamtkosten einer Technologie.

Das Gesamtrisiko dieser Technologie ergibt sich analog zu Formel (0.2). Nachdem man die SD, die Korrelationen und den erwarteten Ertrag jeder einzelnen Technologie kennt, kann man – wieder den Zusammenhängen der vorher dargestellten Portfoliotheorie folgend - Erzeugungsportfolios mit beliebigen Anteilen der verschiedenen Technologien berechnen.

Wie oben erwähnt, müssen zuerst die Variationen (SD) und Korrelationen der einzelnen Kostenkomponenten ermittelt werden. Für die **Brennstoffkosten** werden sie auf Basis von nominellen Zeitreihen [WEO 2000][23] in der Zeitperiode 1989-2000 ermittelt.[24] Im Fall von O&M- und Investitionskosten könnten sie bei Vorhandensein historischer Daten ebenfalls auf diese Weise berechnet werden. Da wir aber momentan nicht über ausreichende Zeitreihen verfügen, schätzen wir sie mit Hilfe von Näherungen aus der Finanzwirtschaft. Wir nehmen dabei an, dass O&M- und Investitionskosten ein ähnliches Muster aufweisen, wie bestimmte finanzielle Instrumente.

Im Fall von **fixen O&M-Kosten** unterstellten wir, dass sie den Schulden einer Firma ähnlich sind [siehe Brealey und Myers (1991) p. 473-474]. Fixe O&M sind von vertragsähnlicher Natur – so lange der Besitzer einer Anlage genug Einkünfte hat, werden die fixen O&M bedient werden. Das ist den Zinsenzahlungen von Unternehmen ähnlich, die auch so lange stattfinden, solange genügend Einkünfte vorhanden sind. Wir verwenden deshalb die von Ibbotson Associates (1998) angegebenen SD von Langzeit-Firmenanleihen als Näherung für die Fluktuationen von fixen O&M-Kosten, d.h. 8,7%.

Für das Risiko von **variablen O&M-Kosten** greifen wir ebenfalls auf eine Näherung aus der Finanzwelt zurück: In der Buchhaltung werden variable O&M-Kosten als volumsabhängig definiert, d.h. in diesem Fall abhängig von den erzeugten kWh. Zusätzlich zur Abhängigkeit vom Stromoutput, der natürlich auch von wirtschaftlichen Zyklen abhängt, werden variable O&M-Kosten auch mit den Arbeits- und Materialkosten fluktuieren, die ebenfalls mit der ökonomischen Aktivität zusammenhängen. Aus diesen Gründen nehmen wir an, dass das Risiko, das mit diesen Kosten verbunden ist, am besten durch das Risiko eines diversifizierten Marktportfolios beschrieben werden kann. Wir ziehen dazu das Marktportfolio von *Standard*

[23] und persönliche Auskunft von Maria Agiri.

[24] D.h. für jeden Brennstoff 12 Werte, Details dazu im Anhang (Appendix A);

& Poors (*S&P) 500* heran.[25] Das Risiko der variablen O&M-Kosten ergibt sich demnach zu 20,1%.

Der Neubau von großen Anlagen bedingt zahlreiche zusätzliche Risiken. Je länger die Planungs- und Bauzeiten, desto größer auch die Wahrscheinlichkeit von Änderungen in den projektierten Kosten. Wie im Fall der variablen O&M-Kosten unterstellen wir hier auch, dass das **Investitions- und Planungskostenrisiko** ähnlich dem eines gut diversifizierten Marktportfolios ist, d.h. eine SD von 20,1% besitzt. Dieses Risiko wird auf alle neuen nicht modularen Anlagen angewendet, nämlich Kohle, Gas, Öl und Nuklear. Im Gegensatz dazu weisen Wind, PV und andere modulare Technologien definitionsgemäß nur wenig Investitions- und Planungskostenrisiko auf. Deshalb wird dieses Risiko in dem Fall Null gesetzt.

Zusätzlich zu den Variationen der Kostenkomponenten sind auch die Korrelationen untereinander zu ermitteln. Im Fall der Brennstoffkosten geschieht das wie oben beschrieben. Ihre Korrelationen sind in Table 0-2 angegeben. Bei den restlichen Kostenarten müssen sie in Ermangelung von ausreichenden Daten geschätzt werden. Um die Unsicherheiten dieses Vorgehens bestimmen zu können, wurde eine Sensitivitätsanalyse durchgeführt, die im Appendix B dokumentiert ist.

Table 0-2 Empirisch ermittelte Korrelationskoeffizienten zwischen den Brennstoffkosten der Technologien[26]

	GAS	KOHLE	ÖL	ANGEREICHERTES URAN	GAS NEU	KOHLE NEU
GAS	-	0.48	0.46	-0.27	-	0.48
KOHLE	0.48	-	0.24	-0.13	0.48	-
ÖL	0.46	0.24	-	-0.37	0.46	0.24
URAN	-0.27	-0.13	-0.37	-	-0.27	-0.13
GAS NEU	-	0.48	0.46	-0.27	-	0.48
KOHLE NEU	0.48	-	0.24	-0.13	0.48	-

In Table 0-3 sind die geschätzten Korrelationen der Kosten angegeben. Sie können wie folgt interpretiert werden: Es wird angenommen, dass für jedes Paar von Technologien *A* und *B* ($A \neq B$) die folgenden Korrelationen gelten:

[25] Genauso gut hätte man auch den *Morgan Stanley MCSI Europe Index* verwenden können.

[26] Da Wind keine Brennstoffkosten besitzt, ist die Korrelation mit jedem anderen Brennstoff Null und deshalb in der Tabelle nicht angegeben. Wie im Anhang (Appendix A) erläutert, werden die Kosten von Ausgleichsenergie in der vorliegenden Studie vernachlässigt.

- Die Korrelation der O&M- bzw. Investitionskosten mit den Brennstoffkosten wird als recht niedrig eingeschätzt. Daher wird hier der Korrelationskoeffizient von variablen, fixen O&M- und Investitionskosten mit den Brennstoffkosten auf Null gesetzt.
- Für zwei Technologien *A* und *B* würde man einen Korrelationskoeffizient von 1,0 zwischen den variablen (bzw. auch den jeweiligen fixen) O&M-Kosten erwarten. Nachdem aber die Variationen der O&M Kosten auch zu einem Teil unsystematisch und zufällig sind, muss der Korrelationskoeffizient kleiner als 1,0 sein. Wir verwenden hier einen Wert von 0,7 als Basisschätzung.
- Genauso wie im vorherigen Absatz ist auch für die Korrelationskoeffizienten der Investitionskosten von zwei unterschiedlichen Technologien *A* und *B* zu argumentieren. Auch in diesem Fall wird ein Koeffizient von 0,7 gewählt.
- Der Korrelationskoeffizient zwischen den variablen und fixen O&M-Kosten wird als relativ niedrig angenommen und daher auf 0,1 gesetzt.
- Der Korrelationskoeffizient zwischen den Investitionskosten und den O&M-Kosten ist ebenfalls als relativ niedrig einzuschätzen und wird auch mit 0,1 gewählt.

Table 0-3 Verwendete Korrelationskoeffizienten zwischen den Kostenkomponenten von zwei Technologien A und B

		Technologie B			
	Kostenkomponente	Investition- und Planung	Brennstoff	Variable O&M	Fixe O&M
Technologie A	Investition- und Planung	0.7	0	0.1	0.1
	Brennstoff	0	Table 0-2[27]	0	0
	Variable O&M	0.1	0	0.7	0.1
	Fixe O&M	0.1	0	0.1	0.7

Die oben angeführten Schätzungen für das Risiko und die Korrelationen von O&M- und Investitions- und Planungskosten sind natürlich irgendwie künstlich und können in der Zukunft verbessert werden. Deshalb wurde auch in Appendix B eine Sensitivitätsanalyse durchgeführt.

Die Anwendung der Portfoliotheorie auf das Subportfolio jeder einzelnen Technologie ist die Vorraussetzung für die nun mögliche Portfolioanalyse des Erzeugungsmix. Das nächste Kapitel präsentiert die Ergebnisse dieser Analyse.

[27] Dieser Korrelationskoeffizient wird auf Basis von historischen Zeitreihen von 1989-2000 geschätzt.

0.4.2. Technisch realisierbare Portfolios

Figure 0-4 zeigt die Ergebnisse der Portfolioanalyse. Die Randbedingungen für die *technisch realisierbaren Portfolios* sind, neben den im Anhang (Appendix A) angeführten, folgende:

Erstens, existierende Anlagen können nur stillgelegt, nicht aber erweitert werden. Anders gesagt bedeutet das, dass die von diesen Anlagen erzeugte Strommenge bis 2010 entweder konstant bleibt, oder sinkt. So kann also z.B. kein vom Modell ermittelter effizienter Strommix für 2010 mehr als 27,5% Kohlestrom enthalten. Dieser Anteil entspricht der Erzeugung von existierenden Kohle-Anlagen im Jahr 2000 (das sind 31,7% am EU-2000 Mix).

Zweitens ist die Windstromerzeugung im Jahr 2010 durch das von Huber et al. (2001) ermittelte Mid-term Potential nach oben hin begrenzt. Es entspricht einem Anteil am 2010-Erzeugungsmix von rund 7,9%.

Die starke konvexe Linie in Figure 0-4 ist die Effiziente Grenze (EG). Sie reicht von Punkt *P* bis zu *100% Gas neu*. Alle Portfolios, die nicht auf dieser Linie liegen, befinden sich rechts von ihr und sind deshalb ineffizient. Zusätzlich zur EG sind die theoretischen Erzeugungsportfolios angegeben, die nur 100% einer bestimmten Technologie enthalten. Dabei ist zu beachten, dass alle Technologien, die mit „neu“ gekennzeichnet sind, zusätzlich zu den Betriebsrisiken auch Investitionsrisiko widerspiegeln. Deshalb liegen diese „neuen“ Technologien immer ein wenig weiter rechts auf dem Graphen, als die entsprechenden „alten“. Gleichzeitig besitzen die neuen Technologien – wie weiter oben beschrieben – auch einen größeren Ertrag (d.h. sie liegen in der Grafik weiter oben), weil ihr Jahresnutzungsgrad höher ist und die Investitionskosten durch Lerneffekte niedriger sind.

100% Öl alt ist die Technologie, die sich am weitesten rechts befindet und damit das höchste Risiko besitzt. Wie schon erwähnt, wird für die Stromerzeugung aus Öl angenommen, dass in Zukunft keine weiteren Kapazitäten mehr gebaut werden. Deshalb findet sich kein „Öl neu“ in der Grafik.

100% Nuklear weist den niedrigsten Ertrag aller Technologien auf. Auch für Nuklear gilt, was für Öl erläutert wurde: es ist in dem hier vorgestellten Modell nicht vorgesehen, dass neue Atomkraftwerke gebaut werden können.

100% Wind ist besitzt ein niedrigeres Risiko als Nuklear und weist außerdem einen höheren Ertrag auf. Aufgrund der Tatsache, dass im Jahr 2000 noch sehr wenig Windstrom erzeugt wurde (etwa 1%)[28], ist *100% Wind alt* in der Grafik nicht dargestellt.[29]

Weiters findet sich auf der Grafik der Stromerzeugungsmix der EU für das Jahr 2000, entnommen aus Electricity Information (2001). Es werden allerdings in dem hier verwendeten Modell nur die konventionellen Technologien (Gas, Kohle, Öl, Nuklear) und - als

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[28] Electricity Information (2001) weist für die EU im Jahr 2000 folgende Stromerzeugungsanteile (vorläufig) aus: Nuklear 33,8%, Kohle 27,1%, Gas 17,2%, Wasserkraft 12,3%, Öl 6,6%, Brennbare Erneuerbare und Abfall 1,9%, Solar & Gehzeiten & Wind 0,9%, Geothermie 0,2%. Insgesamt wurden rund 2.560 TWh Strom erzeugt. Nachdem die Stromerzeugung von Solar- und Gezeitenkraftwerken sehr gering im Vergleich zur Windstromerzeugung ist, wird im Weiteren davon ausgegangen, dass die oben angeführten 0,9% gänzlich aus Windkraftanlagen stammen.

[29] Aus Gründen der Vereinfachung werden für den Ertrag und das Risiko der existierenden Windanlagen auch der Ertrag und das Risiko von Neuanlagen herangezogen.

Repräsentant der Erneuerbaren (siehe weiter oben) - Wind betrachtet. Dieser Strommix wird im Folgenden *EU-2000* getauft. Zusammengenommen produzieren diese 5 Technologien 86% des Stromes in der EU im Jahr 2000.[30]

EU-2010 steht für die Prognose des EU Erzeugungsmix im Jahr 2010 aus Electricity Information (2001). Wie auch für EU-2000 werden hier nur die 4 konventionellen und eine erneuerbare Technologie (Wind) betrachtet. Zu beachten ist hier, dass sich in diesen beiden Fällen die Prozentwerte auf unterschiedliche Strommengen beziehen. Während im Jahr 2000 von den angeführten Technologien rund 2.190 TWh erzeugt wurden, werden für 2010 etwa 2.520 TWh prognostiziert. Alle abgebildeten Mixe - bis auf den von EU-2000 - beziehen sich auf die Prognose der Stromerzeugung für das Jahr 2010.

Wie man erkennen kann, liegen weder EU-2000 noch EU-2010 auf der EG - obgleich recht knapp rechts davon - und sind daher ineffizient. Die Prognose für 2010 weist zwar einen höheren Ertrag, aber gleichzeitig auch ein höheres Risiko als EU-2000 auf. Die Entwicklung vom derzeitigen Mix zum prognostizierten stellt deshalb keine tatsächliche Verbesserung im Sinne der Portfoliotheorie dar.

Würde man statt EU-2010 das Portfolio *N* anstreben, dann erhielte man denselben Ertrag [kWh/Cent] wie EU-2000 aber bei minimalem Risiko. Dieser Mix stellt im Gegensatz zu EU-2000 ein effizientes Portfolio dar. *N* besteht zu rund 17,5% aus Gas alt, 27,5% Kohle alt, 1,4% Öl alt, 34,4% Atomstrom, 7,9% aus Wind, 2,4% Gas neu und 9% Kohle neu.

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[30] In dem vorliegenden Modell geht es in erster Linie um die Untersuchung des Einflusses der konventionellen Technologien. Ein erweitertes Modell soll auch Wasserkraft und Brennbare Erneuerbare inkludieren.

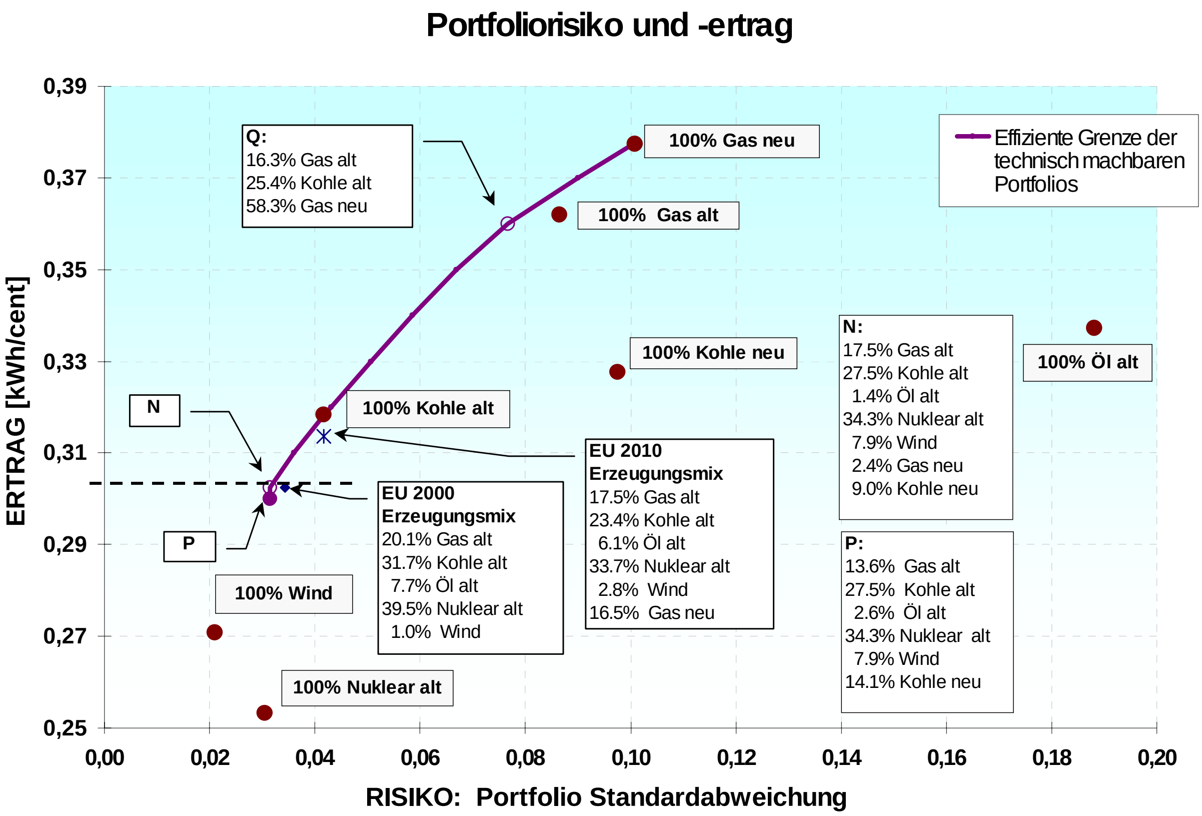

Figure 0-4 Technisch machbare effiziente Portfolios[31]

Wollte man den Ertrag gegenüber EU-2000 erhöhen (gleichzeitig muss man dann aber eine Vergrößerung des Risikos in Kauf nehmen), z.B. so hoch wie im Fall von EU-2010, dann würde sich der effiziente Mix in Richtung von weniger Atomstrom als in *N* und mehr neuen GuD-Anlagen verschieben. Der erzeugte Strom aus Windanlagen bleibt von *P* bis zu einem Ertrag von etwa 0,35 kWh/Cent stets am oberen Maximum von 7,9%. Diese Entwicklung entlang der EG ist auf Figure 0-5 gut nachzuvollziehen. Punkt *Q*, der in beiden Grafiken (Figure 0-4 und Figure 0-5) zu finden ist, stellt den Mix dar, ab dem kein Wind mehr in der EG enthalten ist: bei größerem Ertrag als *Q* bestehen die effizienten Erzeugungsportfolios nur mehr aus Gas neu, Kohle alt, und Gas alt.

Es ist nun Sache der jeweiligen Entscheidungsträger anhand dieser Grafik einen beliebigen Ertrag für das Erzeugungsportfolio zu wählen. Man erhält dann sofort den dafür effizienten Mix und das damit verbundene Risiko.

Betrachtet man Figure 0-5 noch einmal genau, dann stellt man fest, dass der Anteil von Atomstrom in der Effizienten Gerade von *P* in Richtung höhere Erträge stets abnimmt und bei einem Ertrag von 0,35 kWh/Cent Null erreicht. Ein Anteil von 0% Atomstrom im Jahr 2010 ist allerdings politisch nicht machbar. Dieses Ergebnis entsteht deshalb, weil in dem aktuellen Modell für eine Stilllegung von Anlagen weder zusätzliche Kosten noch Risiken anfallen. Das

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[31] Beachten Sie, dass sowohl EU 2000 als auch EU 2010 nur ein Mix aus vier konventionellen und einer erneuerbaren passiven Technologie (nämlich Wind) sind. Wie bereits erläutert, finden in dieser Studie Wasserkraft, Biomasse, usw. keinen Eingang.

mag im Fall von existierenden GuD-Anlagen und Kohlekraftwerken durchaus annähernd der Praxis entsprechen, weil diese zum Teil nur konserviert werden, um sie im "Fall des Falles" wieder zu neuem Leben zu erwecken. Diese Tatsache trifft allerdings nicht auf Atomkraftwerke zu. Daher wird im nächsten Kapitel eine politisch machbare Lösung untersucht.

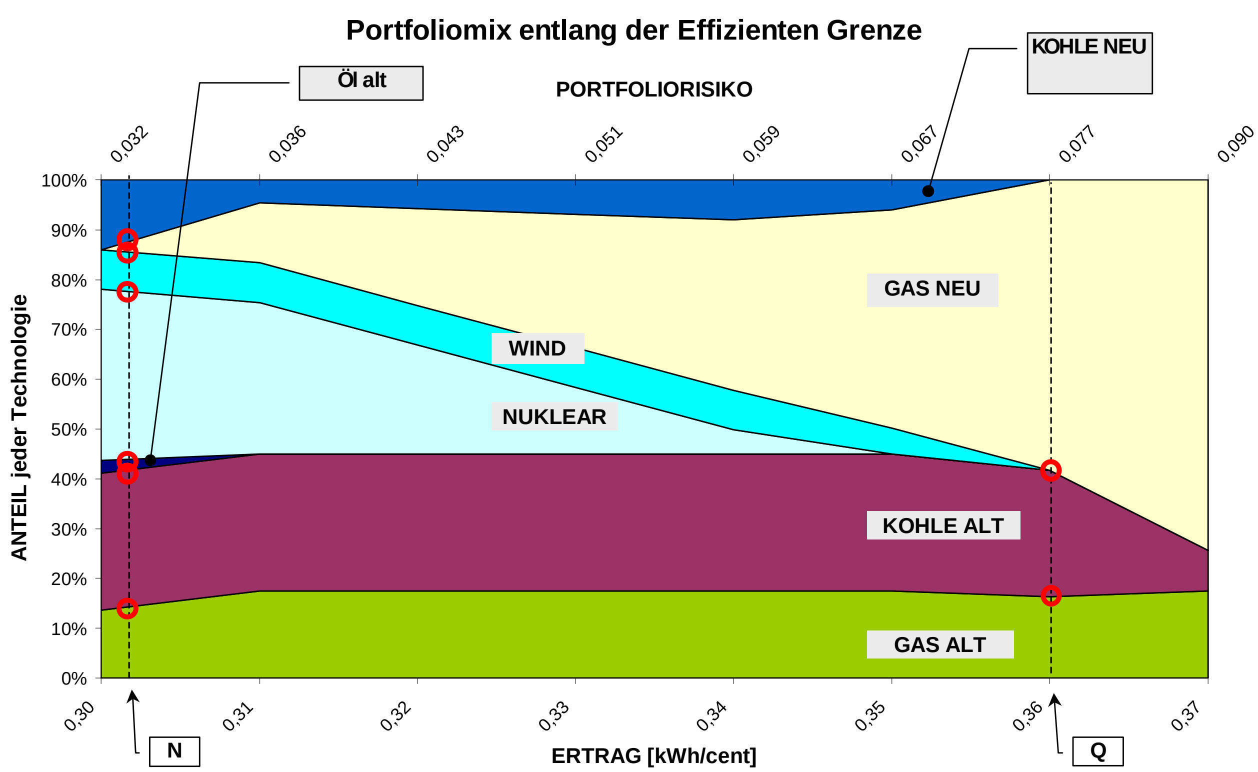

Figure 0-5 Portfoliomix entlang der Effizienten Grenze der technisch realisierbaren Portfolios

0.4.3. Politisch machbare Portfolios

Da ein Anteil von 0% Atomstrom am Stromerzeugungsmix für 2010 politisch nicht machbar ist, wird in diesem Kapitel eine *politisch machbare Effiziente Gerade* (PEG) vorgestellt. Diese ist durch die Annahme spezifiziert, dass im Jahr 2010 gleich viel Atomstrom produziert wird, wie im Jahr 2000.[32] Das bedeutet auch, dass im Jahr 2010 in der PEG bei jedem Ertragslevel 34,3% Atomstrom enthalten sind.

Wie in Figure 0-6 gezeigt, weicht die PEG deutlich von der EG ab. Sie liegt weiter rechts und birgt deshalb ein höheres Risiko. Je höher das Ertragsniveau desto größer auch die Abweichung der beiden voneinander. Der Punkt *W* besitzt den selben Ertrag wie *V* aber weist

[32] Dieses Vorgehen stellt nur eine Annäherung an die politischen Gegebenheiten dar. In einem zukünftigen Modell wird diesem Faktum durch Berücksichtigung der Stilllegungskosten und –risiken Rechnung getragen.

ein um rund 15% höheres Risiko auf. Vergleicht man die verwendeten Technologien in den beiden Portfolios, so stellt man fest, dass *W* deutlich weniger Kohle (4,1% in *W* vs. 27,5% in *V*), mehr Atomstrom (34,3% vs. 13,4%), mehr Gas neu (45,5% vs. 26,8%) und keinen Wind enthält.

Außerdem bewirkt das Festhalten an der derzeitigen Atomstromproduktion eine deutliche Reduktion des maximal möglichen Ertrages verglichen zur technisch durchführbaren Lösung aus dem letzten Kapitel. Während der Maximalertrag vorher bei 0,378 kWh/Cent lag (Punkt *100% Gas neu* in Figure 0-6), kann nun nur 0,335 kWh/Cent erreicht werden (Punkt *E*). Bei diesem Maximalertrag enthält der effiziente Mix rund 34,3% Atomstrom und 65,7% Gas neu.[33]

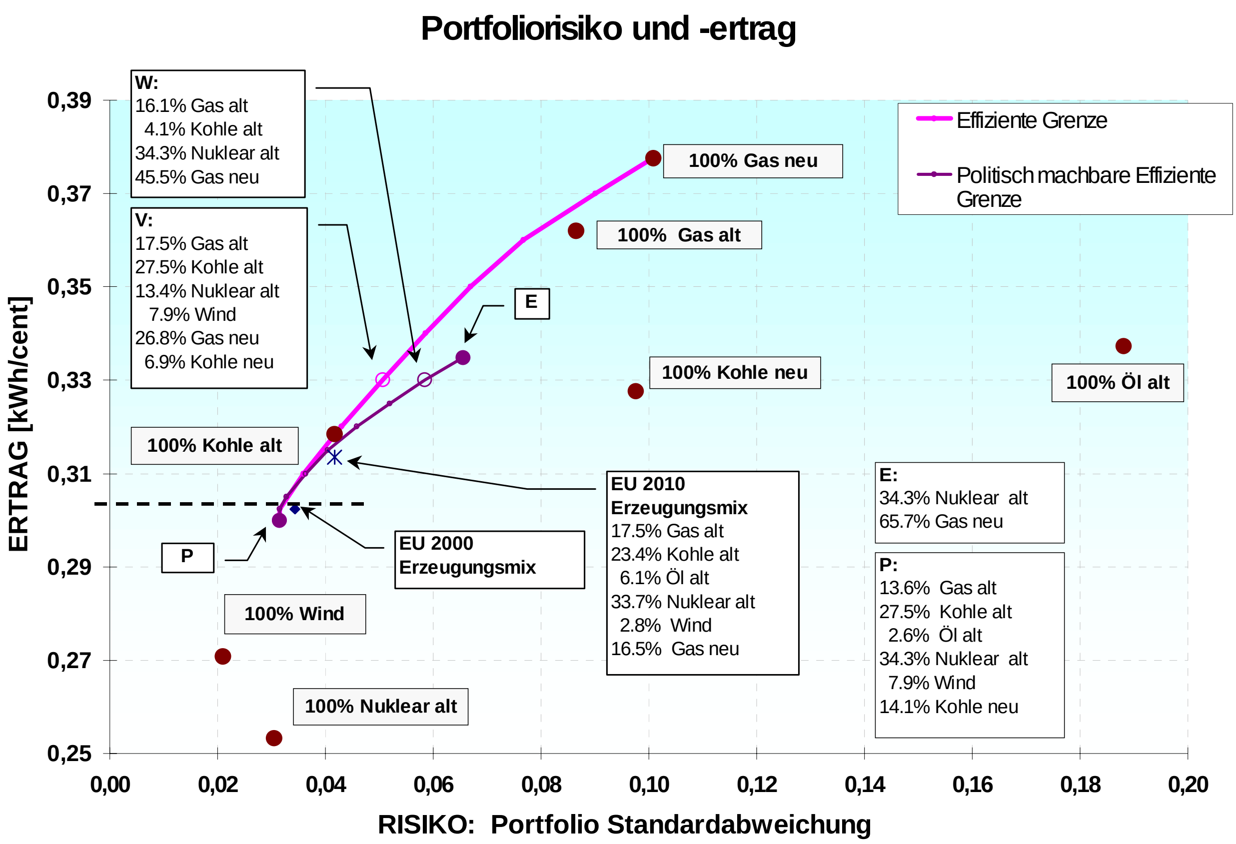

Figure 0-6 Politisch machbare effiziente Portfolios[34]

[33] Den Autoren ist bewußt, dass sich realistischerweise nur etwa 10% der Erzeugungskapazität bis 2010 ändern wird. Deswegen sind natürlich Extremlösungen wie z.B. 34% Strom aus alten Atomkraftwerken und 67% aus neuen Gasanlagen politisch ebenfalls nicht machbar. Im Folgenden werden jedoch diese Lösungen a priori nicht von der PEG ausgeschlossen.

[34] Beachten Sie, dass sowohl EU 2000 als auch EU 2010 nur ein Mix aus vier konventionellen und einer erneuerbaren passiven Technologie (nämlich Wind) sind.

Figure 0-7 zeigt die Stromerzeugungsportfolios entlang der PEG. Die Tatsache, dass die Menge produzierten Atomstroms gleich bleibt, bewirkt bei höheren Erträgen vor allem eine Senkung des Anteils an Wind, Kohle alt und Kohle neu.

Allerdings kann der EU-2000 Mix - wie zuvor auch - verbessert werden, indem mehr Wind in das Portfolio integriert wird. Der Punkt, der denselben Ertrag wie EU-2000 aufweisen würde und auf der PEG liegt, beinhaltet - genauso wie im Fall der EG - 17,5% Gas alt, 27,5% Kohle alt, 1,4% Öl alt, 34,3% Atomstrom, 7,9% Wind, 2,4% Gas neu und 9% Kohle neu.

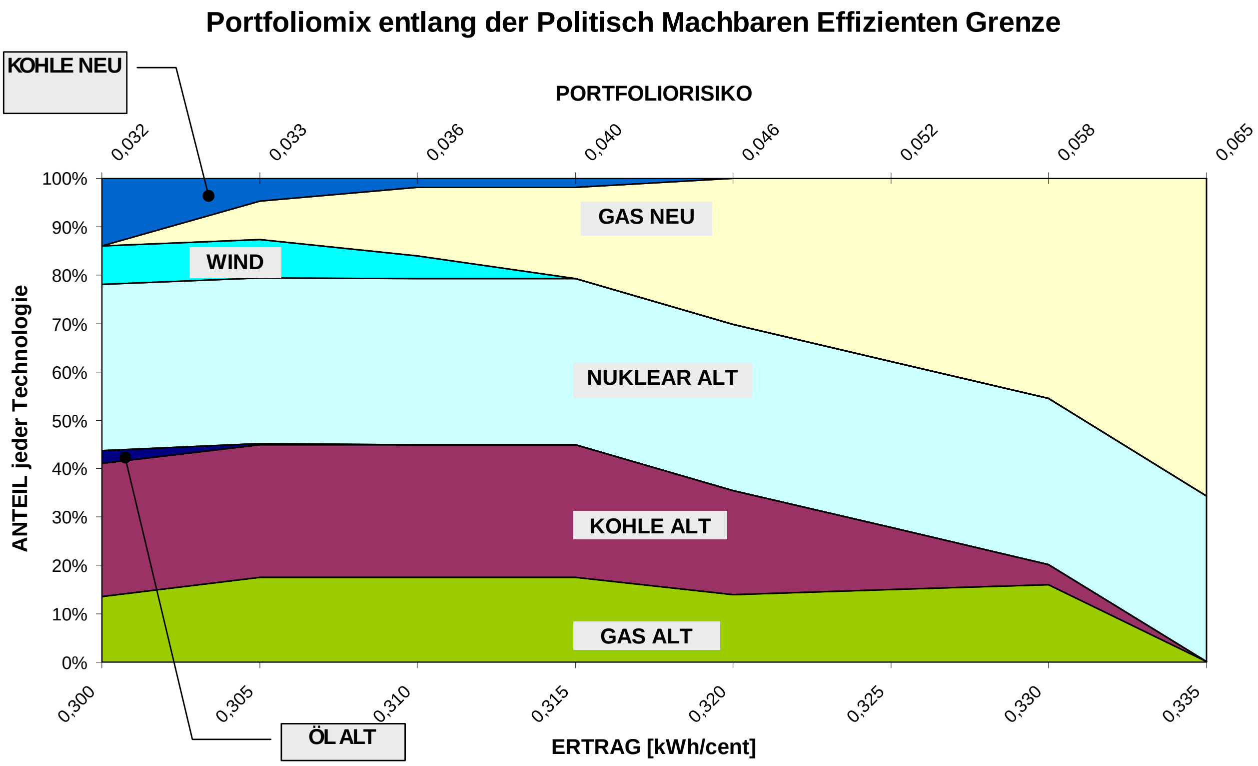

Figure 0-7 Portfoliomix entlang der Politisch Machbaren Effizienten Grenze

0.5. Wichtige Ergebnisse und Schlussfolgerungen

Unsere Ergebnisse legen deutlich nahe, dass politische Entscheidungsträger im Energiebereich die Folgerungen dieser Mittelwert-Varianz-Portfolioanalyse in Betracht ziehen. Diese Entscheidungsträger sind derzeit u.a. mit folgenden wichtigen Themen beschäftigt:

- **Versorgungssicherheit:** Während „Versorgungssicherheit" heute häufig als Synonym für die Vermeidung von großflächigen Versorgungsunterbrechungen verwendet wird, haben wir einen subtileren und – nach unserer Meinung – wichtigeren Aspekt für diesen Bereich definiert. Großflächigen Versorgungsunterbrechungen sind natürlich teuer und unattraktiv, aber Steigerungen in Brennstoffpreisen und Volatilität sind auch relativ teuer und bewirken ökonomische Verluste, die in die 10.000 bis 100.000 Mrd. € gehen können.

- **Energiediversifikation:** Wie Versorgungssicherheit ist auch die Energiediversifikation nicht explizit definiert. Ein weit akzeptiertes Ziel scheint jedenfalls zu sein, robuste Energiemixe – d.h. effiziente Portfolios – zu bilden, die Preisrisiko unter verschiedensten Bedingungen minimieren.
- **Erschwingliche und verlässliche Strompreise:** Die Bildung einer erschwinglichen Elektrizitätsversorgung impliziert, Portfolios mit bekannten Kosten- und Risikocharakteristiken zu schaffen.

Die MV-Portfoliooptimierung kann in allen drei genannten Bereiche zur Analyse herangezogen werden. Versorgungssicherheit zu garantieren mag eine Reihe von Faktoren betreffen. Einer ist auf jeden Fall die Diversifikation der Versorgung weg von Technologien, die aus politischer Sicht unzuverlässig sind. Ebenso wichtig ist es sicherzustellen, dass das Europäische Stromerzeugungsportfolio in dem Sinne effizient ist, dass es die Volatilität (Risiko) bei einem gegebenen Strompreislevel minimiert.[35] Portfoliotheorie ist das einzige quantitative Mittel, das Effizienz eines Portfolios untersucht und gleichzeitig garantiert, dass Diversifikation und Erschwinglichkeit / Verlässlichkeit gegeben sind.

Die vorgestellte Mittelwert-Varianz-Portfolioanalyse zeigt - unter den im Anhang (Appendix A) angeführten Randbedingungen und Einschränkungen - deutlich, dass sowohl der aktuelle als auch der prognostizierte Stromerzeugungsmix für das Jahr 2010 von einer Ertrag-Risiko-Perspektive suboptimal sind. Ihre Effizienz kann dadurch verbessert werden, dass verstärkt passive erneuerbare Technologien (hier Wind) in das Portfolio integriert werden.[36]

Präziser gesagt, die Ergebnisse deuten an, dass eine Erhöhung des Erzeugungsanteils von Windstrom auf bis zu 7,9%[37] die Portfolio-Stromgestehungskosten unter den gegebenen

[35] Es wird unterstellt, dass die Strommarktpreise sich auf lange Sicht an den Stromgestehungskosten orientieren.

[36] In dieser Analyse werden externe Kosten nicht berücksichtigt. Würde man sie in die Portfolioanalyse miteinbeziehen, dann ist anzunehmen, dass der Anteil Erneuerbarer in der Effizienten Grenze wesentlich höher läge. Im Appendix B (B.3) wird das Ergebnis einer Portfolioanalyse vorgestellt, die Risiko-korregierte Kosten für Technologien heranzieht. Das führt zu weit höheren Anteilen an Windstrom in der EG als in den hier vorgestellten Fällen.

[37] Dieser Prozentwert entspricht dem Windstrom "mid-term" Potential für das Jahr 2010 nach Huber et al. (2001).

Randbedingungen im Vergleich zu EU-2000 nicht erhöht. In vielen Fällen senkt eine Einbeziehung von mehr Wind sogar die Portfoliokosten (d.h. erhöht den Ertrag) und das Risiko.

Zum derzeitig massiven Trend in Richtung GuD-Anlagen ist aus Sicht der Portfoliooptimierung zu sagen, dass ein größerer Anteil von neuen GuDs zwar zu einer Steigerung des Ertrages führt, allerdings gleichzeitig auch mit erhöhtem Risiko verbunden ist.

1. Introduction[38]

Energy diversification and security are like the weather: many people talk about these issues, although no one can fully control the future events that affect them. However, unlike the weather, certain energy security related risks can be controlled to some extent. Along these lines, standard mean-variance portfolio techniques can help policy makers evaluate the costs and the risks of alternative generation portfolio options, thereby helping create efficient portfolios that best meet the goals of energy diversification and energy security.

Portfolio analysis, a part of contemporary finance theory, is widely used by financial investors to create robust portfolios that produce efficient outcomes under various economic conditions. Efficient portfolios do not create unnecessary risk relative to their expected returns. Stated differently, efficient portfolios are defined by the following twin 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 guide policy makers towards developing effectively diversified generating portfolios with known risk levels that are commensurate with their expected overall electricity generation costs. Efficient generating portfolios, therefore, minimise society's energy price risk. This is a crucial aspect of energy security.

Energy security considerations are generally focused on the threat of abrupt supply disruptions,[39] although we argue for the inclusion of a second, more profound aspect: i.e. the risk of unexpected fossil fuel 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 quite clearly suggests that fossil price fluctuation depress economic activity in fossil fuel-importing nations. Even small percentage increases in fossil prices can yield sizeable economic losses through unemployment and income losses, as well as losses in the value of financial and other assets.[40] 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.

Portfolio Analysis Versus Least Cost Planning

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 to correctly

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[38] We would like to acknowledge the helpful comments provided by John Michael Byrne and Andrew C. Stirling.

[39] See e.g. Green Paper "Towards a European strategy for the security of energy supply" [European Community 2001]

[40] Given the estimates in this literature, such economic losses can rise to the tens and even hundreds of billions of US dollars; see: Sauter and Awerbuch (2002). An excellent recent survey of this literature can also be found in: Papapetrou (2001); see also Sadorsky (1999) Yang, et al. (2002) and Ferderer (1996).

identify the 30-year "least cost" option. Least cost procedures are roughly analogous to trying to identify 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 economic 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, the astute combination of alternatives serves 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 renewables 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.[41] 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 can serve to reduce overall portfolio cost and risk even through their stand-alone generating costs may be higher. This somewhat counter-intuitive result derives from basic finance theory and is caused by the correlation of the costs and risks of generating alternatives. 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.*

The Analytic Approach

The analysis presented here uses classical mean-variance portfolio analysis that focuses on generating costs and their risks, i.e. the historic variance of the outlays for fuel, operation and maintenance (O&M) and construction period activities. The analysis is applied to a mix of traditional generating technologies — coal, oil, gas, and nuclear — as well as wind. [42]

Portfolio analysis examines market or "cost" risk of resource alternatives. However, we note that electricity markets may exhibit short-term price fluctuations that are driven by factors such as the exercise of strategic behaviour and market power by participants as well as random daily events that include generator outages and weather extremes. These factors are not reflected in the mean-variance analysis.

This paper 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 considers only fuel price risk, 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,

[41] Portfolio theory is generally attributed to Nobel Laureate Harry Markowitz (1952) as discussed subsequently.

[42] We assume that each technology can - independent of its location and type - feed into the electricity grid. Moreover, we do not consider any transmission constraints in the grid.

O&M as well as construction period risk on the basis of the historic standard deviation (SD) of their "holding-period-returns"[43] and their interrelationship or *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.

[43] Holding period returns are discussed in Section 2.

2. The Approach – Portfolio Basics[44]

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. 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*[45] portfolio return, to σ_p, the total portfolio risk, defined as the standard deviation of past returns.[46] 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:

$$E(r_p) = X_1 \bullet E(r_1) + X_2 \bullet E(r_2) \qquad (3.1)$$

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, σ_p, is also a weighted average of the two securities, but is tempered by the correlation coefficient between the two returns:

$$\sigma_p = \sqrt{X_1{}^2\sigma_1{}^2 + X_2{}^2\sigma_2{}^2 + 2X_1X_2\rho_{12}\sigma_1\sigma_2} \qquad (3.2)$$

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[44] Parts of this section appeared previously in Awerbuch (1995b) and Awerbuch (2000).

[45] In the case of perfect markets, expectations are assumed to be unbiased, but not error-free.

[46] As measured by the financial holding period return [Seitz (1990) p. 225]: $r_s = \frac{EV - BV + CF}{BV}$ where *EV* is the ending value, *BV* the beginning value and *CF* the "cash inflow during period";

Where:

ρ_{12} is the correlation between the two return streams[47], and

σ_1 and σ_1 are the standard deviations of the holding periodic returns to asset *1* and *2* respectively.

2.1. The portfolio effect

Properly designed portfolios yield a *portfolio effect* - risk reduction attained through diversification. Figure 2-1 illustrates the portfolio effect in the case of two financial assets whose returns have a correlation coefficient of ρ = 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*[48] 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*[49]) 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*. 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*.

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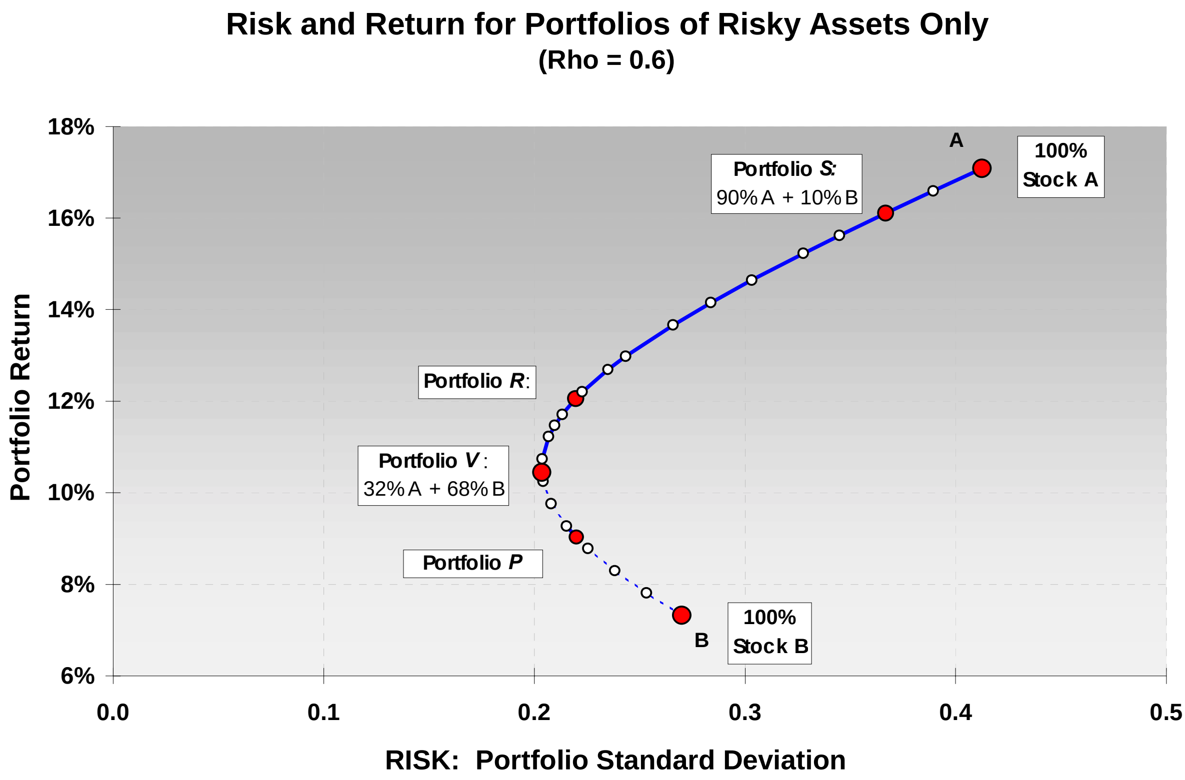
[47] The covariation of two return streams can be calculated by $COV_{12} = \rho_{12}\sigma_1\sigma_2$. Therefore equation 3.2 might as well be written as $\sigma_p = \sqrt{X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + 2X_1X_2COV_{12}}$.

[48] 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).

[49] 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.



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

Figure 2-1 Portfolio Effect

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 2-2 illustrates this effect.

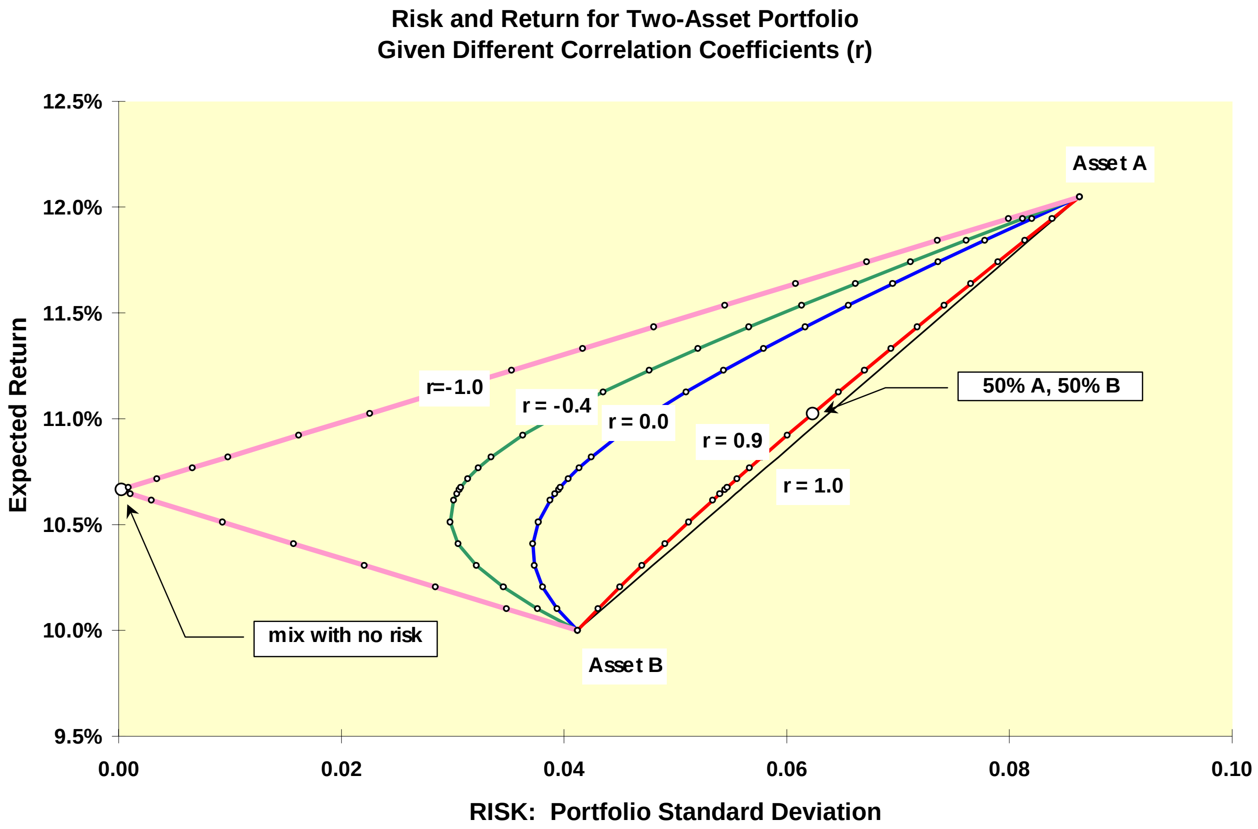


Figure 2-2 Risk and return for two-asset portfolio given different correlation coefficients

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[50] 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.

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,[51] 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. Such a portfolio would always provide the same expected return, since when returns of *A* were rising, returns of *B* would fall by an equal amount.

[50] The costs of gas and coal in the US over the last 25 years exhibit this correlation coefficient -- details see later.

[51] This is the historic US coal-gas cost correlation for the years 1990-99, details see later.

2.2. Efficient portfolios in the presence of riskless assets

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.[52] 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.[53] For this reason T-bills are more properly called *zero-beta* assets[54], to distinguish the fact that they are not truly free of risk, but are riskless when the returns are expressed in a particular manner.[55] 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 PV and wind alternatives that to some extent mimic the financial "risklessness" of T-bills.[56]

Figure 2-3 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 2-1. The new element in Figure 2-3 is the straight line, which represents the risk-return combinations for portfolios consisting of risky *and* riskless assets.[57] Point *M,* the tangency point between the line and the curve, now becomes the

[52] Fama and French (1998) show that US treasury obligations are an appropriate risk-free asset for European financial portfolios.

[53] Although investors are virtually certain to ultimately receive the face value at maturity;

[54] 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.

[55] 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.

[56] 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.

[57] 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 illustrated as follows using equation 3.2. If asset *1* is risk free, then $\sigma_1 = 0$ and $COV_{12} = 0$ so that portfolio risk, σ_p becomes $\sigma_p = \sqrt{X_2^{\,2}\sigma_2^{\,2}} = X_2\sigma_2$ which is a straight line.

optimal mix of risky assets (*M* consists of 60% A plus 40% *B*).[58] 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 the portfolio *M.*[59] As more T-bills are added, the risk/return point moves down the line (each tick mark represents a 25% change) 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 2-3.

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 does not) but is considerably less risky.[60] This illustrates that by including lower-yielding but riskless assets, we can create a portfolio that produces the same expected return— 9%— but cuts 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.[61] 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.

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[58] The tangency point M is the portfolio mix that maximises the portfolio performance θ

$$\theta = \frac{E(r_p) - r_f}{\sigma_p}$$

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

[59] This means that Portfolio *H* consists of 50% T-bills, 30% *A* and 20% *B*.

[60] *P* is below *V* and therefore not efficient.

[61] The gain from such moves can be even more sizeable depending on the relative risks of *A* and *B* and the risk-free rate of return. The fact that these moves are possible serves to illustrate why *M* is the optimal mix of *A* and *B*.

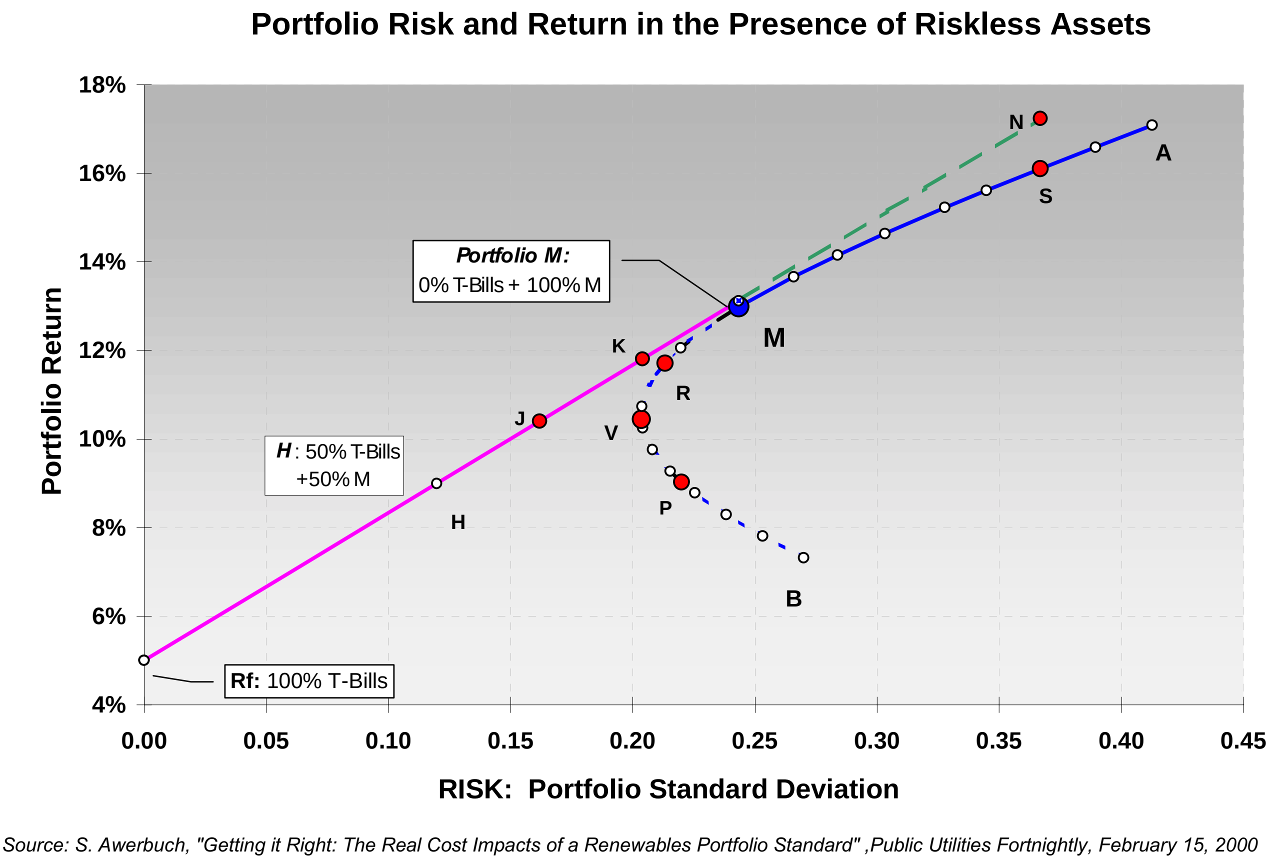

Figure 2-3 Efficient portfolios in the presence of riskless assets

2.3. The case of multiple assets: The efficient frontier

The portfolio selection methods outlined above for the two-asset portfolios can easily be extended to portfolios of three or more securities or assets.[62] Figure 2-4 is a standard representation of the risk/return possibilities. By mixing securities in different proportions, infinite risk-return combinations can be found as illustrated by the 'X' marks in Figure 2-4. Each X represents an individual portfolio.

None of the interior portfolios are efficient since other mixes are available that yield portfolios whose risk/return lies to the left and above. The latter represent optimal combinations of risk and return, i.e. at a selected return level they exhibit the minimum risk attainable. The efficient portfolios all lie on the convex *efficient frontier*, shown as the heavy curve *BD* in Figure 2-4. The expected return of an efficient portfolio can be increased only by increasing

[62] The mathematical formulation is then extended following the scheme for two securities (see equation 3.2), 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 $2.X_i.X_j.COV_{ij}$. Therefore, for three securities equation 3.2 becomes

$$\sigma_p = \sqrt{X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + X_3^2\sigma_3^2 + 2X_1X_2\rho_{12}\sigma_1\sigma_2 + 2X_1X_3\rho_{13}\sigma_1\sigma_3 + 2X_2X_3\rho_{23}\sigma_2\sigma_3}$$

Equation 3.1 is extended to $E(r_p) = X_1 \bullet E(r_1) + X_2 \bullet E(r_2) + X_3 \bullet E(r_3)$

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 with 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).

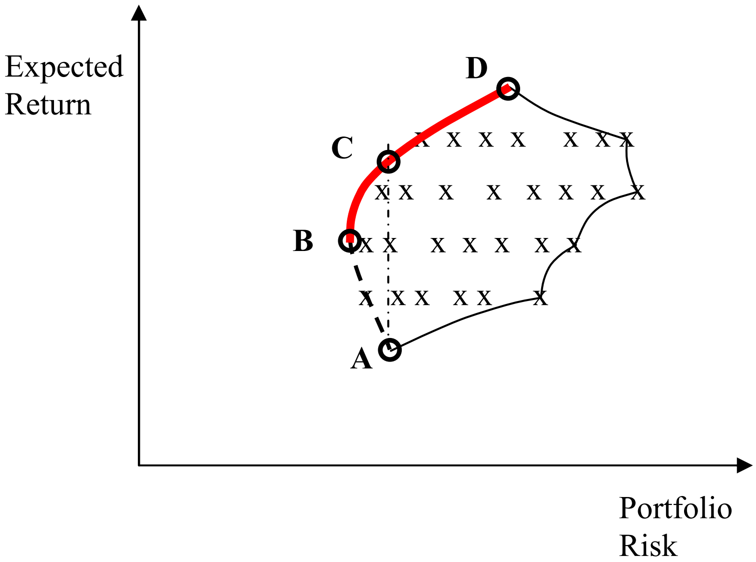

Figure 2-4 Efficient frontier of a portfolio with more than two risky securities

2.4. Introducing a risk free security to mix of multiple risky assets

Adding a riskless asset to the risky portfolio (see above) produces important results as already discussed.

Figure 2-5 illustrates the effects of adding a riskless security, e.g. T-bills, to the mix of multiple risky assets. The efficient frontier of Figure 2-4 has not changed its shape below the point M. It now lies along the line M-r_f. This straight-line element in Figure 2-5 represents the risk-return combinations for portfolios consisting of risky *and* riskless assets as previously described. 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 the 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.*

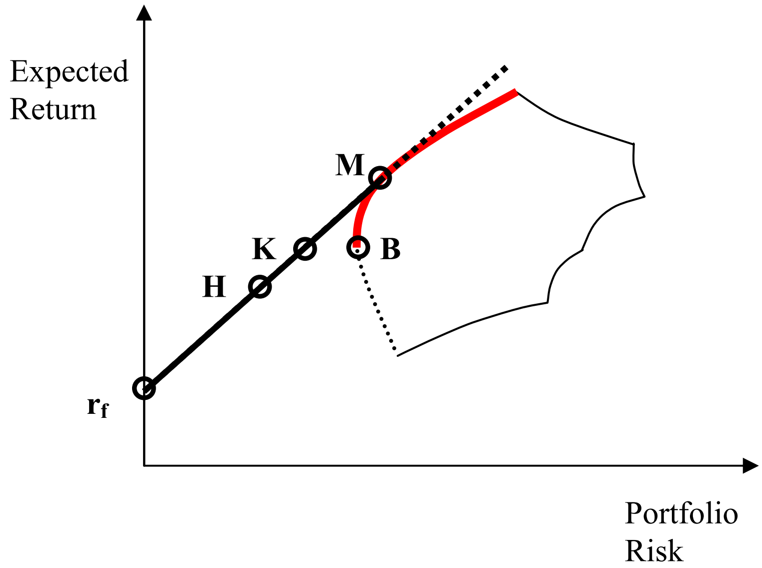

Figure 2-5 Portfolios with risky securities and a riskless asset

The powerful impact that riskless assets have on the portfolio is even clearer in the multiple asset case. For example, portfolio *K,* which consists partly of riskless securities, has the same expected return as portfolio *B* (which consists entirely of equity stocks or other risky securities) but is significantly less risky. This further illustrates that by including lower-yielding riskless assets a portfolio can be created that produces 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.

2.5. Analysis of generation portfolios

The relationships derived from financial portfolios are applicable to portfolios of generating asset. 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)[63] of costs of the technologies considered [see e.g. Awerbuch (2000)].[64] These include conventional generating technologies (coal, oil, gas, nuclear) and renewables, such as PV, wind and hydro.

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 be violated in the case of a portfolio of generating or other *real* assets.[65] 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 they are relaxed. The standard portfolio assumptions require the existence of *perfect markets* for trading assets, which generally implies low transactions costs, perfect information about all assets and returns that are normally distributed.[66]

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, considerations such as location and fuel availability may affect asset selection, which means that generating assets are not entirely *fungible* or substitutable, as theory would assume (see Appendix A).

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

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[63] See Footnote 46: $r_s = \frac{EV - BV + CF}{BV}$ -- In the case of fuel prices *CF* is zero, *EV* is the fuel price per unit (kWh) in period *t* and *BV* its price in period *t-1*. 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*.

[64] 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 Appendix A.

[65] For details on assumptions and limits affecting the analysis of generation portfolios see Appendix A.

[66] “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].”

Helfat (1988) states that the simple normality assumption is sufficient to enable the portfolio choices of expected utility maximisers to be analysed in terms of mean and variance. Yet, she applies this method to symmetrical distributions that are not necessarily normal. 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.

however, or for the analysis of national generating portfolios, the lumpiness of individual capacity additions becomes relatively less significant since total capacity needs are larger.

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. Seitz, (1990), Helfat (1988), Herbst (1990)].

2.6. Ignorance and Diversity Vs the Mean-Variance Approach

Andy Stirling (1994) rejects the applicability of mean-variance portfolio theory. He differentiates among three basic *states of "incertitude",*

i. **risk**: "a probability density function may meaningfully be defined for a range of possible outcomes"

ii. **uncertainty**: "there exists no basis for the assignment of probabilities"

iii. **ignorance**: "there exists no basis for the assignment of probabilities to outcomes, nor knowledge about many of the possible outcomes themselves…"

Arguing that *ignorance* rather than *risk* or *uncertainty* dominates real electricity investment decisions, Stirling conceptualizes diversification as a response to ignorance. Indeed this notion forms the basis of his adaptation to energy use of the *Shannon-Wiener Diversity Index* [Stirling 1994][67] that has attracted considerable interest.

Stirling rejects the applicability of mean-variance portfolio theory on the following grounds.[68]

1. A portfolio theoretic approach treats the incertitude to which diversity is a response entirely as 'risk' and thus as tractable to probabilistic characterisation. This effectively amounts to a denial of the relevance of strict uncertainty and ignorance (under which, by definition, probabilistic approaches are inapplicable). Effectively, a portfolio theoretic approach is ruling out the relevance of surprise.
2. A portfolio theoretic approach is based on stylised assumptions about some very specific aspect of performance – such as fuel prices. Yet serious 'surprises' can be mediated in many other forms. For instance, 'energy shocks' can take the form of interruptions due to factors such as warfare, terrorism, natural catastrophe, organisational collapse, infrastructure failure, engineering fault or regulatory intervention. These kinds of issues are major elements in the rationale for diversification. But they are effectively excluded by a portfolio-theoretic approach based on fuel prices.
3. The recommended approach would focus directly on the diversity of the portfolios in question rather than on highly structured assumptions about performance variabilities. This would better reflect the indeterminate character of the sources of ignorance and uncertainty to which diversity is a response.

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[67] Sometimes called the *Stirling Diversity Index,* e.g. see: *Toward a Sustainable Energy Future*, Paris, IEA/OECD, 2001, p. 91

[68] Personal correspondence with Andrew C. Sterling, 2002

There is merit in the argument that "surprise" rears itself in wars, international incidents and other events that may have no historic precedent. Yet, we would take exception to the idea that surprise, which is a "major element[s] in the rationale for diversification", is "effectively excluded by a portfolio-theoretic approach based on fuel prices." *Portfolio risk* is generally 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 many individual portfolio components, which have a wide variety of historic causes including 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, it seems to us, is therefore the summation of the effects all historic events, including countless historic surprises.[69]

It may be true, as Stirling posits that no particular random event may ever be precisely duplicated. Nonetheless, at least in the case of equity stocks, historic total variability is widely considered to be a useful indicator of future volatility. Along these lines we agree 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]."

Indeed we would argue that this situation is no different in the case of 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.[70] 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.

We therefore conclude as follows[71]: Our focus is on (probabilistic) total risk, which will still not reflect possible future 'surprise'. (Readers may find it useful to reference Shackle's work on non-probabilistic risk). The foregoing therefore suggests that there may still lurk surprises out there that cannot and have not been reflected by our historic SD estimates, and which may someday rear their (ugly?) heads. We however, choose to focus on that which is probabilistically tractable.

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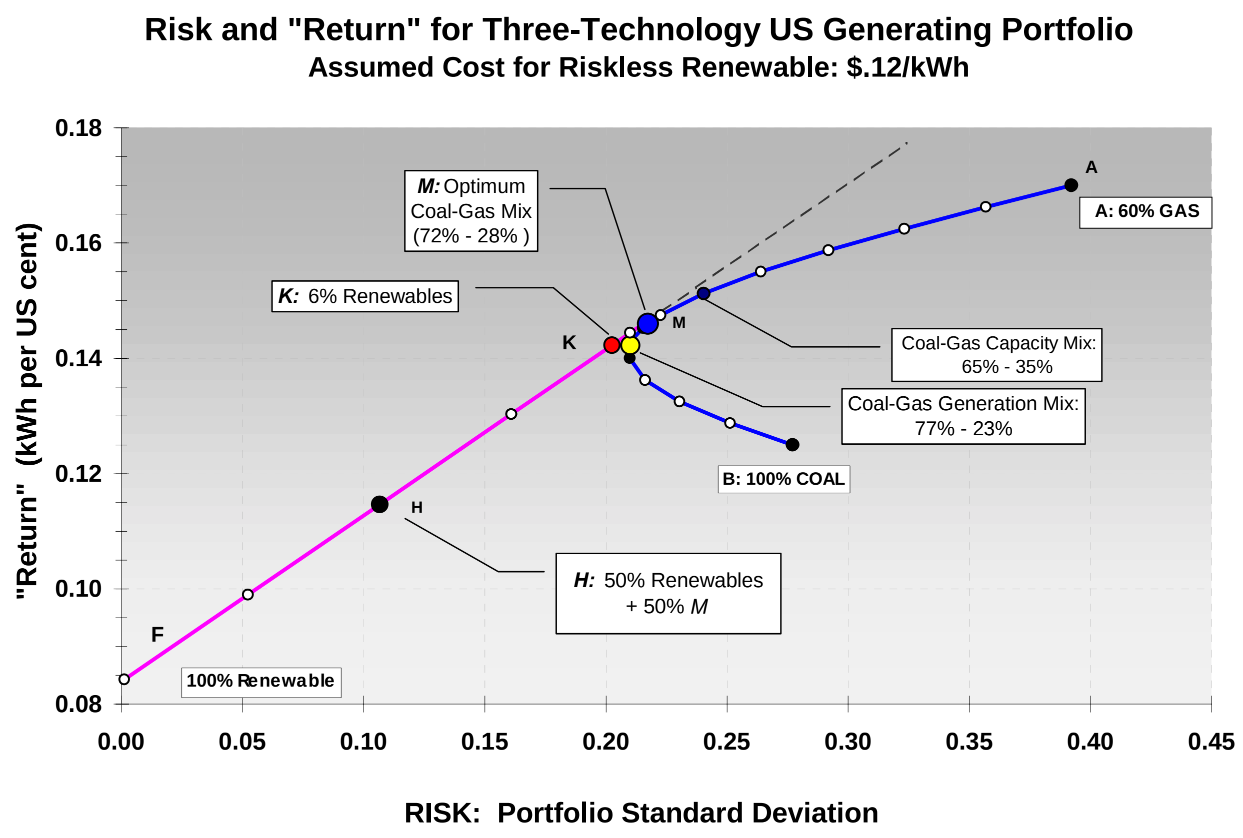
[69] On of our reviewers disagrees that our SD estimates include future surprise. This is further discussed in Appendix A.

[70] e.g. Strebel Paul, *Breakpoints: How Managers Exploit Radical Business Change.* Harvard Business School Press, 1992

[71] Based on further helpful discussions with John Byrne.

2.7. Survey of Previous Results: US Generating Portfolio

Figure 2-6 shows the illustrative result of the previous analysis [Awerbuch 2000] of the US generating portfolio. It is based on return-risk results for a portfolio that includes only two fossil fuels: gas and coal.[72]



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

Figure 2-6 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.[73]

The minimum variance of the fossil portfolio (.21) occurs at a mix consisting of 77% coal and 23% gas.[74] After this point, further gas additions increase both risk and return until a 100%

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[72] Costs are converted to expected returns by simply inverting them. The unit of portfolio return therefore is kWh/cent. For risk appraisal HPRs of fuel prices are used. For details see Section 2.5 and 3.

[73] 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.

[74] Each tick mark represents a 5% change in mix on the fossil portfolio.

gas portfolio is obtained (Figure 2-6 is truncated at 60% gas – 40% coal for illustration purposes).

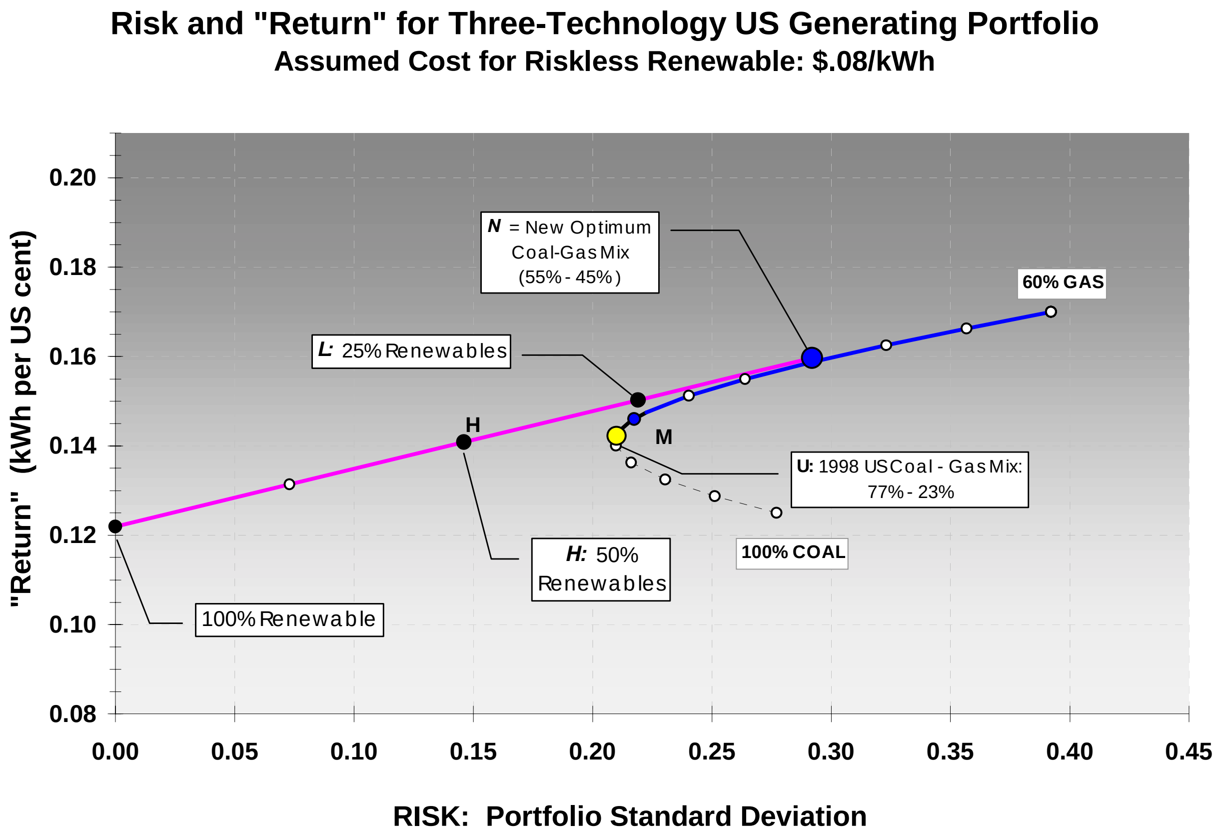
The straight-line segment represents portfolios consisting of the mix *M* combined with a riskless resource mix (with an assumed cost of $0.12 USD/kWh).[75] This is analogous to the previous case of financial portfolios. At *F,* (lower left) the portfolio consists of 100% passive riskless renewables.[76] Finally, at *M*, the portfolio consists entirely of the fossil mix.

The main results of the US analysis are:

1. 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.
2. If generating costs of $.12/kWh are assumed for the renewables bundle (which could consist of a mixture of, for example, wind, photovoltaic 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.
3. 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 2-7.

[75] This might be a passive renewable technology that does not exhibit fuel risk. For further details see the discussion in Section 3.1.

[76] Each tick mark along the line segment represents a 25% addition of the fossil mix *M*.



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

Figure 2-7 Portfolio theory applied to the US portfolio – renewables 0.08 $/kWh

3. Risk/Return Analysis of the EU Generating Portfolio

The analysis is now extended to Europe, using the expanded model that incorporates the risk of O&M and construction period costs.[77] 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,[78] 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 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.

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.

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[77] The assumptions and limits affecting the analysis of generation portfolios are summarised in the Appendix A.

[78] The current version of the Microsoft Excel™ spreadsheet model accommodates maximal nine technologies.

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 returns.[79] The unit of *expected portfolio return* for generation assets becomes kWh/cent.

Moreover, risk appraisal for financial portfolios is based on the *holding-period-returns* (HPR) of securities. In analogy to financial returns, historic fuel and other costs are also converted to periodic HPRs. 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.

3.1. 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 correlations with the other cost types of this technology as well as their respective weightings[80] are used for risk appraisal. The risk for this sub-portfolio is calculated using the portfolio procedures from the preceding sections. The costs of one technology will covary 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 capital and no fuel or O&M costs.

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[79] 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 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.

[80] As a percentage of total levelised generation costs of a technology.

Passive renewable technologies, such as PV or wind, have no fuel costs and therefore do not bear fuel risk.[81] Moreover, due to their high modularity, availability and short lead-times their construction period risk can be neglected as well [e.g. Brower et al. (1997), Hoff (1997) and Venetsanos et al. (2002)].

3.2. Calculating the Efficient Frontier

Lagrange multipliers are often used in the analytic formulations of efficient frontiers,[82] although optimisation procedures are also available and practical. For example, the expanded portfolio model finds the optimal or efficient portfolio set using Microsoft Excel™ SOLVER, which employs an iterative procedure to plot the minimum risk portfolio combination for each level of return.[83]

The next section focuses on portfolios consisting of conventional technologies— coal, gas CCGT, nuclear and oil— and wind.[84]

Risk is initially based solely on fuel price risk, computed on the basis of annual data for the period 1994 – 2000.[85] Section 5 takes the analysis further by also including O&M risk. Section 6 completes the discussion by including investment and planning period risks, which affects only new capacity.[86] The inclusion of investment period risks necessarily makes sense only where existing capacity is differentiated from new capacity. The results of Section 6 are

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[81] 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)].

[82] For the principal methodology see e.g. Copeland and Weston (1988) p. 119

[83] For details see Kwan (2001).

[84] 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 it will be looked at other renewables indicated in the “renewables directive”. 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.

[85] The time period was chosen to better show the *portfolio effect* with three technology mixes. For all successive analysis the time period 1989-2000 is used because we assume that the latter is a less biased guide to the future.

[86] Investment and planning costs are already sunk and do not expose investors to risk.

therefore considerably more complete in certain respects and have more meaningful interpretations for policy making.

4. Case I: Efficient Portfolios reflecting fuel cost variability only

4.1. Three conventional technologies

For expository purposes, we begin the discussion with a simplified case that reflects only fossil fuel price risk for three conventional technologies. 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. The generation costs for the CASES I and II are shown in Table 4-1.[87] The analysis of this report is based on WEO (2000) costs.

However, in order to test the sensitivity of results with different costs we first used risk-adjusted costs based on Awerbuch (2002) for all technologies - see Appendix B.3. Second, we replaced the WEO (2000) wind costs with those based on the EU-Project ElGREEN [Huber et al. 2001] - see Appendix B.4.

Table 4-1 Levelised annual costs of technologies (WEO 2000) for CASES I and II

LEVELIZED COST cent / kWh	CCGT – Gas fired	Steam boiler – Coal fired	Oil[88]	Nuclear	Wind
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
Total busbar cost	**2.76**	**3.14**	**2.96**	**3.95**	**3.97**
Return (kWh/cent)	**0.362**	**0.318**	**0.337**	**0.253**	**0.252**

[87] To put it differently, for the sake of exposition, the weighting associated to fuel variation is 100%. 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). In the case of steam coal the percentages shift a little bit in favour of capital investments, 39.5% investment costs, 42.5% fuel costs, 9% variable O&M and 9% fixed O&M. Hence, in order to make the analysis of the following sections comparable to the actual one the weighting of gas and coal fuel risk should be 66% and 42.5% respectively.

[88] Based on own calculations;

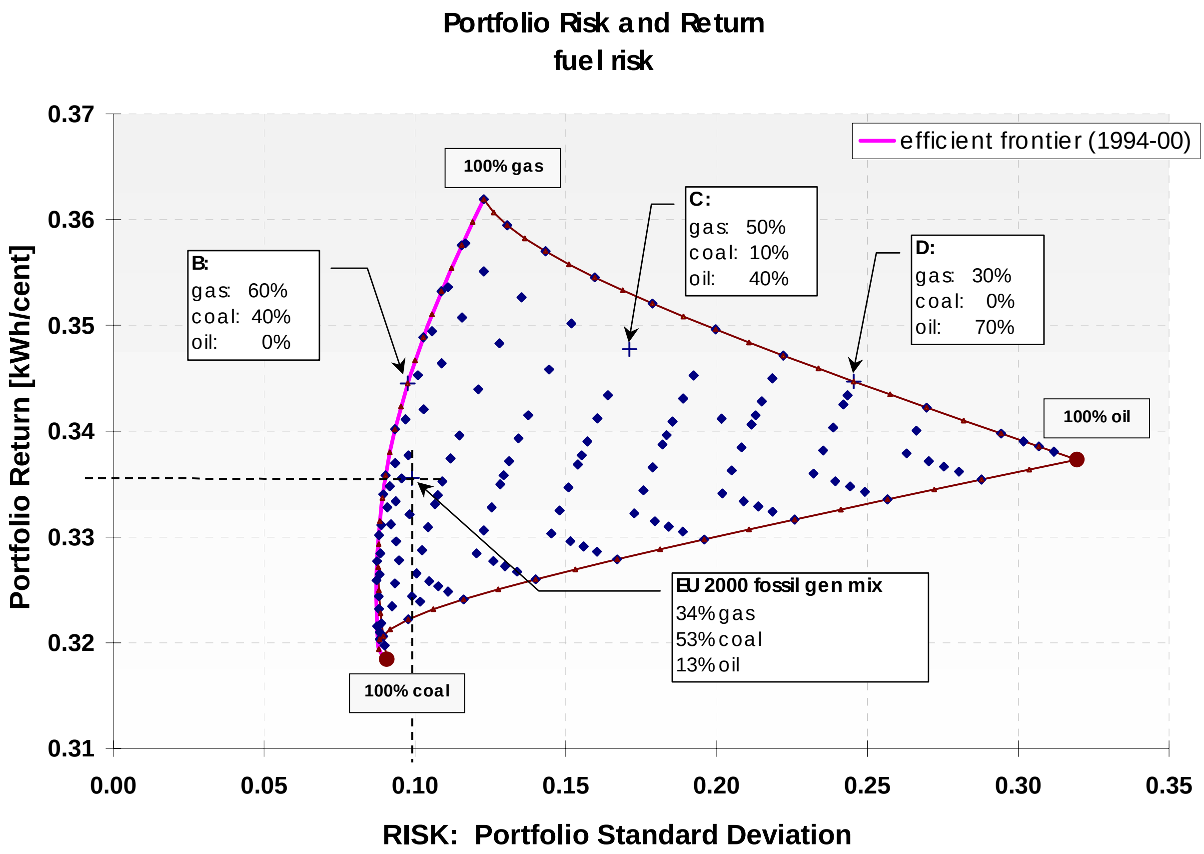

Figure 4-1 Portfolios of three conventional technologies applied to the EU – fuel risk

Figure 4-1 shows the risk and return for portfolios consisting of various combinations of the three technologies, coal, gas and oil.

The graph can be interpreted as follows. A portfolio consisting entirely of oil has a return of 0.337 kWh/cent (equivalent to a generating cost of 2.96 cent/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/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.[89] 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 possible combinations of the three technologies. Whereas only two-technology

[89] Note that the coal- gas line is equivalent to the portfolio curve in Figure 2-6 for the two-technology US portfolio.

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 4-2 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 4-2 has lower risk and equal return to 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* (discussed in Section 2.1.) 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.

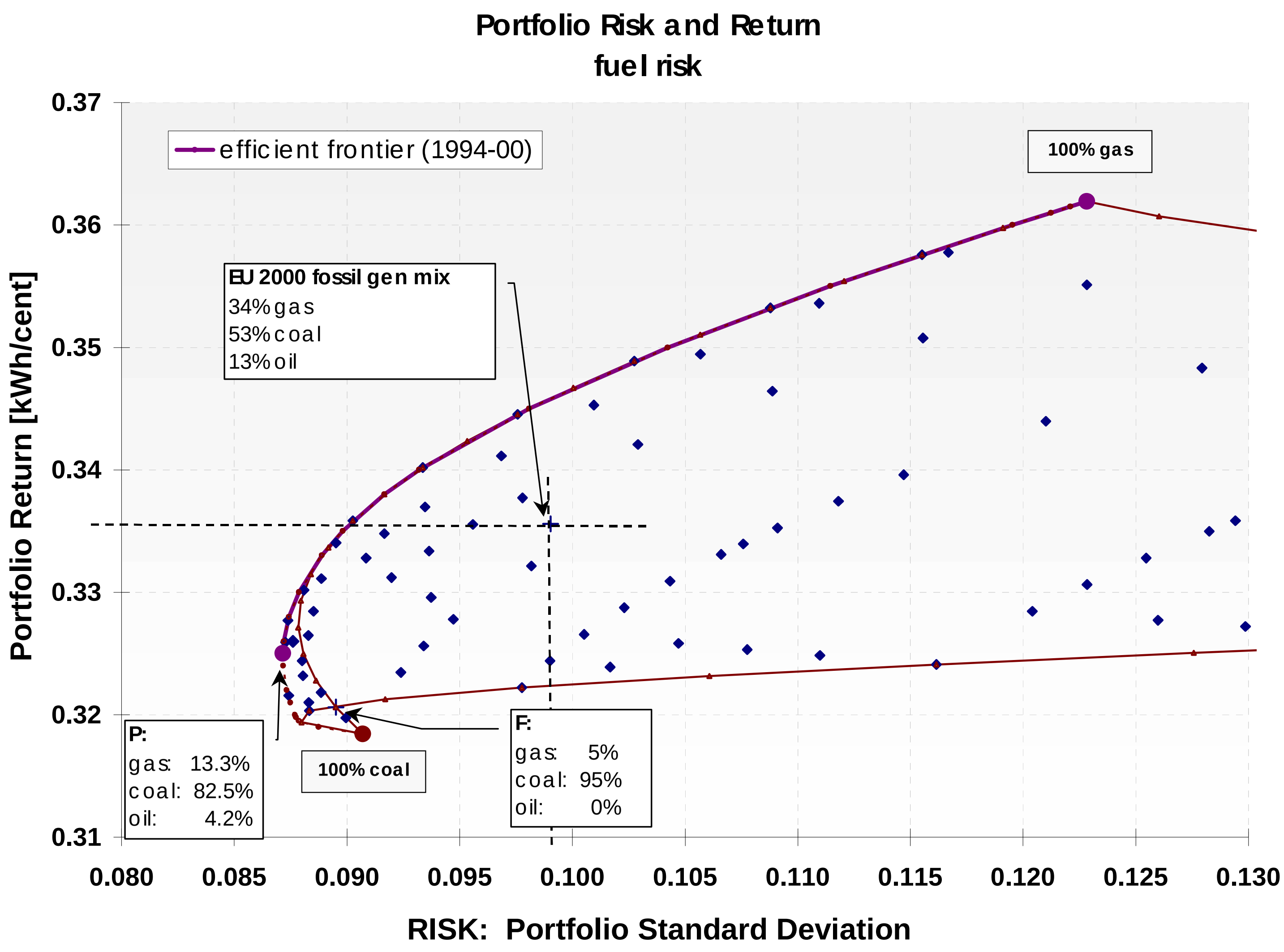

Figure 4-2 Detail of portfolios of three conventional technologies applied to the EU – fuel risk

4.2. Four conventional technologies

Next, we introduce **nuclear generation,** the technology that dominates the actual EU electricity mix, into the portfolio.[90] 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, the assumption that fuel encompasses most of the technology's risk cannot be sustained.[91] 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 market place for uranium or 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.[92]

Given these issues, the analysis proceeded as follows. In a first step, risk is limited to the costs of fuel delivered to power plants. In the next section, additional risk drivers are included. The outcomes of this section are therefore mainly expositional and illustrative.

Historic time series data for natural uranium, conversion and enrichment costs were summed, taking account of their relative individual weightings.[93] Next, periodic HPRs were computed.[94] 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

[90] 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 there 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.

[91] 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 Appendix A).

[92] Personal communication Mr Peter Wilmer, Nuclear Energy Agency;

[93] The variations add up according to equation 3.2.

[94] 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).

might be considered as 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)].[95]

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 4 cent/kWh. We continue to represent this "bundle" with wind because this resource in particular is widely accepted and rapidly growing (see footnote 84). 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 4-3.[96] As before, the light-weight lines show the location of the two-technology-portfolios. The efficient frontier is the solid convex (pink) 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 levels, higher returns are obtainable above the point *P*.

As before, the point *M* is the optimal mix of the risky conventional technologies. The mix at point *M* consists of 41% gas, 42% coal, 17% nuclear, 0% oil and 0% wind. 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 assumed cross correlation estimates, Table 4-2.

Table 4-2 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	-

[95] 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 cost-less and may not be riskless. For further details see Awerbuch (2000), and Pethick and al. (2002)

[96] The remaining analysis is based on historic data for the period 1989-2000. We scaled the portfolio risk in this section (Case I) to be different from the following ones, relatively overstating fuel risk. See also footnote 87.

Figure 4-3 provides useful insights to the risk-return of current and projected EU 2000 conventional generation mix (EU-2000 CON).[97] 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.[98] Recall that *M*, the tangency point of the risk free line with the efficient frontier, represents the optimal mix of the risky assets (see footnote 58).

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, although this level does not reflect any potential network or other issues, and is based solely on the portfolio risk-return developed using the standard mean- variance approach.

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—now the straight segment or riskless asset line-, policy makers can make a range of efficient risk-cost tradeoffs. Some of these tradeoffs, however, may be influenced or limited by political practicalities and other considerations not reflected in this analysis. This is discussed next.

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[97] In this part of the analysis only those four are considered. Together they make up about 85% of the actual generation, see footnote 90.

[98] For a different risk free technology point *R* could shift to the left or to the right.

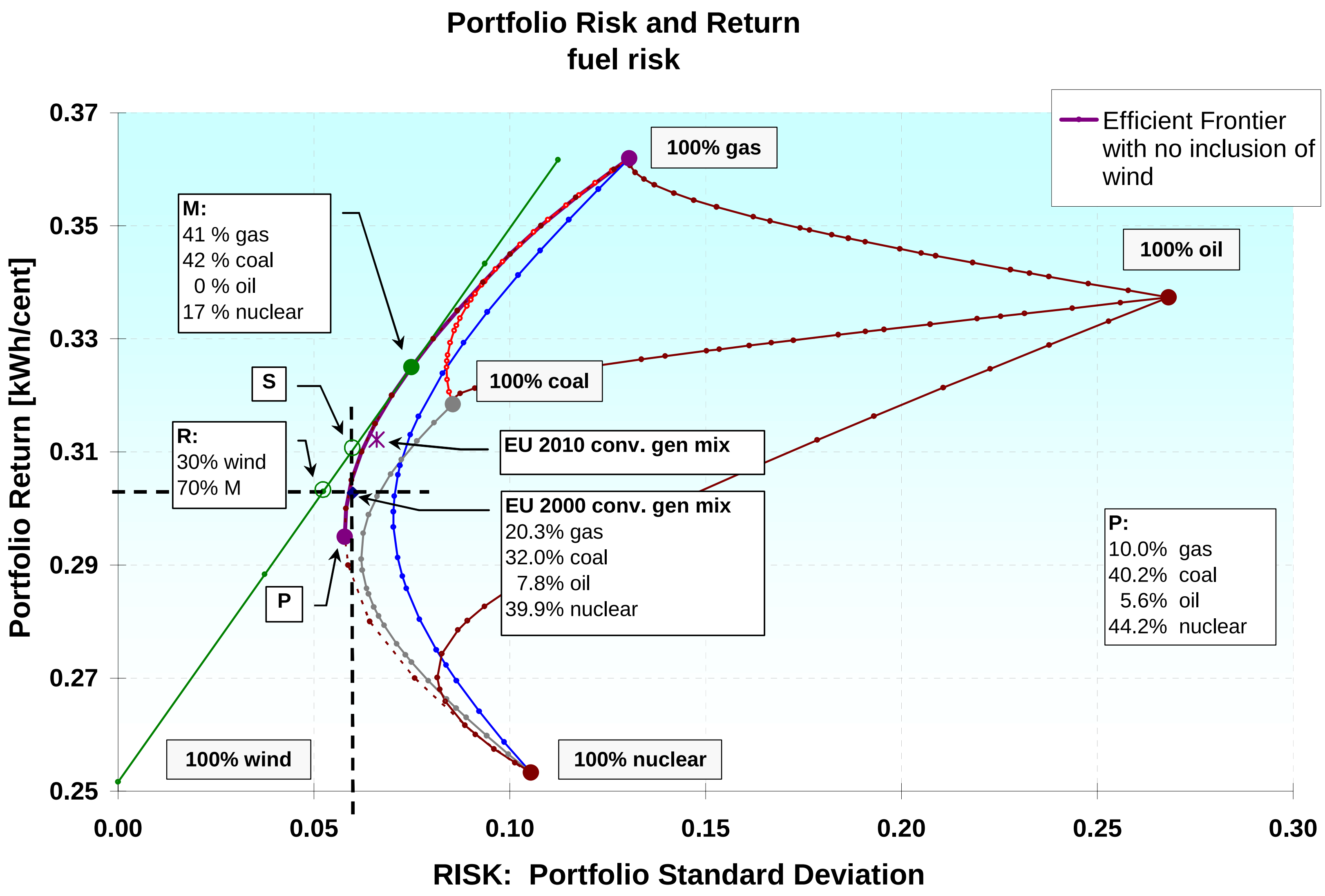

Figure 4-3 Portfolios of four conventional technologies applied to the EU – fuel risk

Optimality and Political 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, political and other constraints may alter the efficient solutions presented. For example, the politically 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 politically more feasible than those of the last section, and evaluates the extent to which these solution affect risk and return.

Figure 4-4 shows the projected EU 2010 CON mix [prepared by Electricity Information (2001)]. This 2010 mix can reasonably be assumed to correspond to a politically based strategy for the next decade.[99]

Compared to the EU-2000 CON, the EU 2010 CON mix is riskier and offers higher returns (lower costs). 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-2010 CON-mix is less than efficient in the sense that both its risk *and* return can be improved by altering 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 politically feasible, 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”, leads to significantly lower risk / return than with EU2010 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 4-5, 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. For example, an infinite number of portfolio mixes can be constructed to yield an overall return of 0.295 kWh/cent – costs of 3.4 cent/kWh. However, as shown in Figure 4-3, the **optimal** or minimum risk

[99] Note that the EU-2010 mixes are based on a different generation level than the EU-2000 generation portfolio.

(conventional) portfolio at this return level, *P*, contains about 10% gas, 40% coal, 6% oil and 44% nuclear.

Stated differently, Figure 4-3 and Figure 4-4 depict the shape of the efficient frontier– i.e. the cost of trading off return against risk, while Figure 4-5 shows the conventional technology changes required to make these risk/return trade-offs.

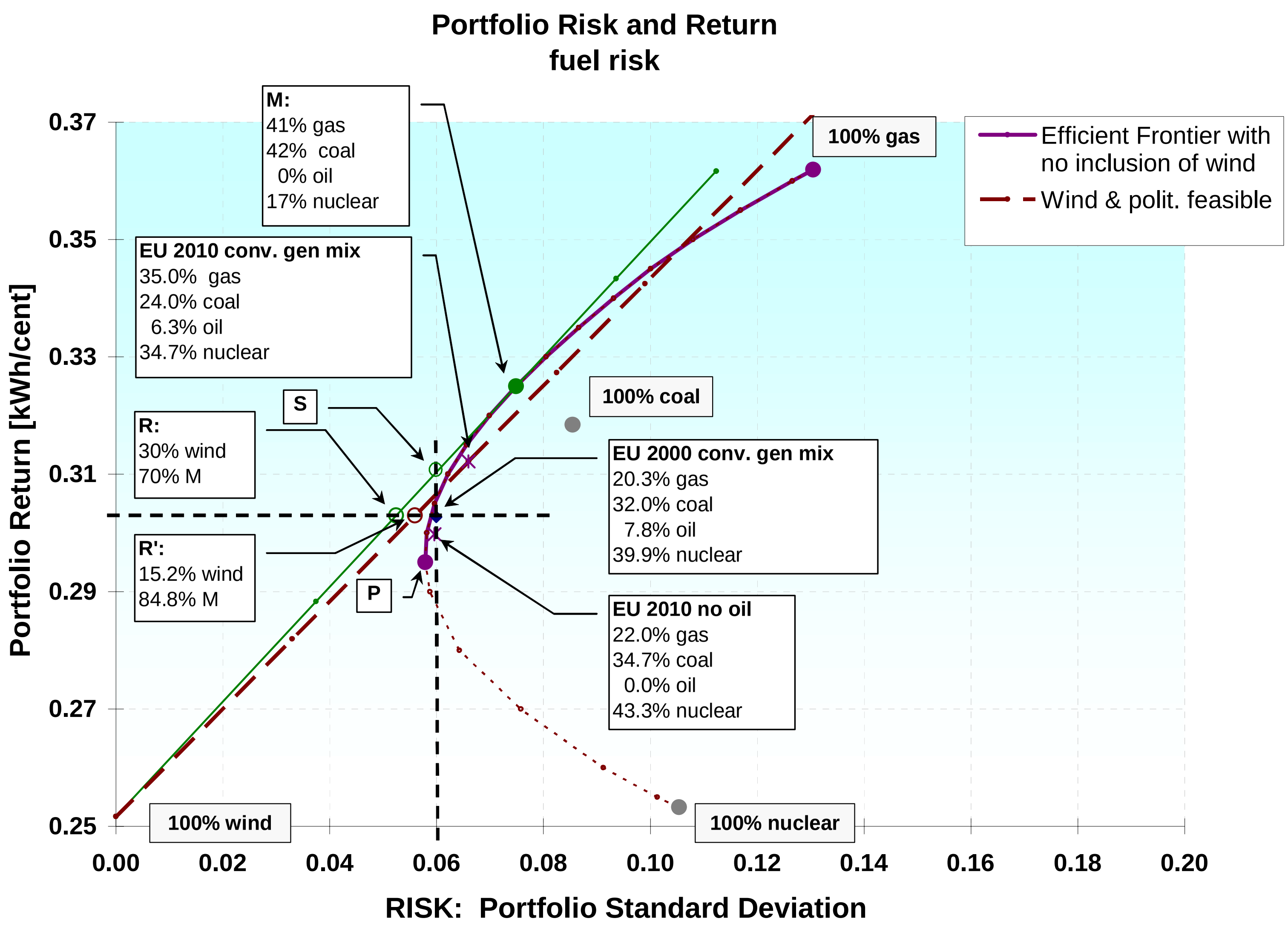

Figure 4-4 Politically feasible solutions

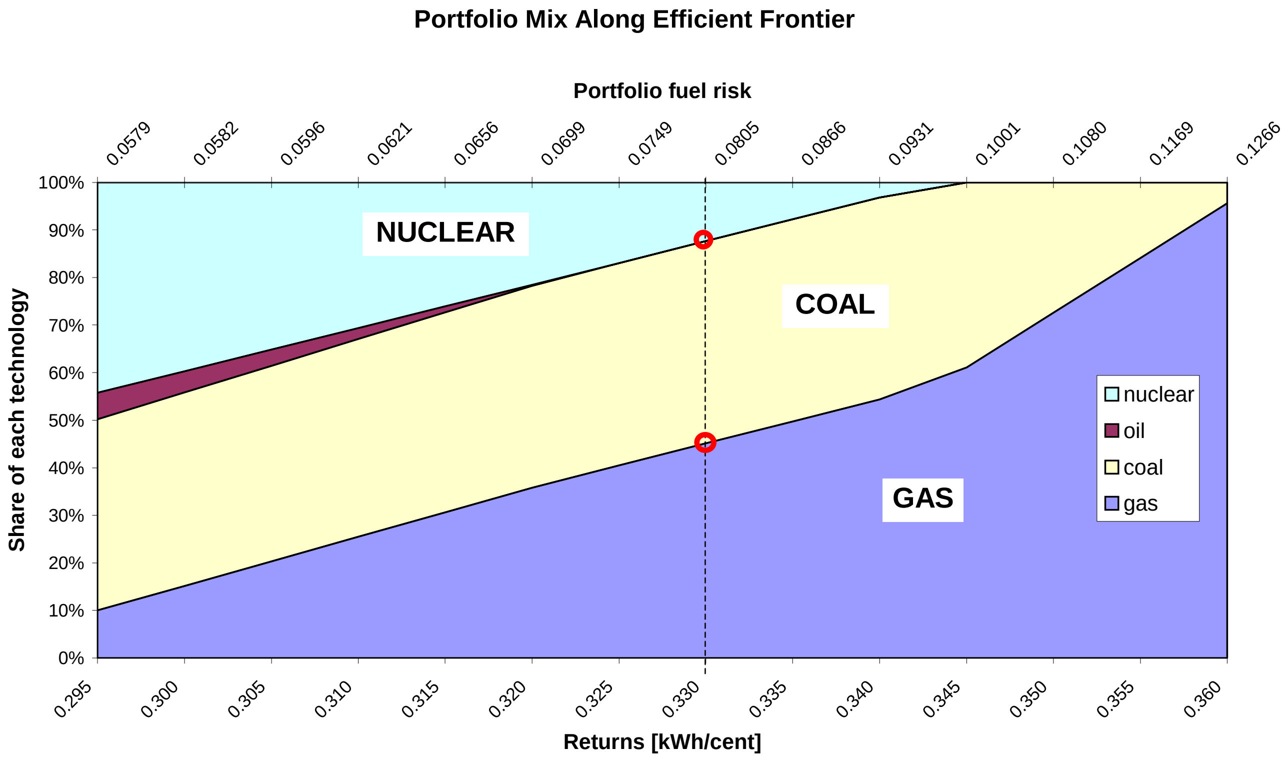

Figure 4-5 Portfolio mix along the efficient conventional frontier - fuel risk

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.

5. Case II: More realistic Applications: Reflecting O&M variability and Construction Period Risks

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.[100] 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 6 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.

5.1. 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 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.[101] As

[100] Salvage and decommissioning costs are not considered and will be included in subsequent studies (see Appendix A).

[101] To be precise, interest payments are somewhat less risky than O&M outlays since available income will be used to first cover these payments.

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 5-1.

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 5-1).

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 Appendix B.

The financial proxy data used to estimate O&M variability is given in Table 5-1, which shows the historic standard deviation of 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 percentage points to a high of 9.2 percentage points % depending on the source and time period.

Table 5-1 Standard deviations of different assets[102]

Time Period	mean[103] [%]	SD [%]	Type of Security	Source
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)**[104]	**New York University, Leonard N. Stern School of Business**[105]
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 5-2 shows the estimated standard deviations for a set historic labour cost data for various countries. The three data sources must be compared with caution since the analysed time periods, the sectors, the groups and the statistical methods and definitions used are different for each. This being said, the calculated standard deviations are in the range of 5.2%, with the exception of data for Austria.

For analysis presented in this report, we use the financial proxy estimates and, as previously mentioned, coupled with sensitivity analyses, (see Appendix 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**.**

[102] Not inflation adjusted total returns,; percentages (%) are "percentage points"

[103] Arithmetic mean

[104] Weighted index of 500 stocks often used as an estimation of the performance of the whole market.

[105] http://www.stern.nyu.edu/%7Eadamodar/pc/datasets/histretSP.xls, last accessed 17 Jun. 02

Table 5-2 Standard deviations of labour costs[106]

Time period	Mean [%]	σ [%]	Specifications	Commentary
1987-1996	2.36	2.13	USA	ILO (2001): **annual nominal data**, sector "Electric light & power", analysed occupation "labourer"
1985-1997	3.44	1.55	Germany	
1985-1997	3.78	9.69	Austria	
1995-2001	1.09	5.2	wages & salaries	EUROSTAT NEW CRONOS Database: **quarterly nominal data,** not seasonally adjusted, sector "Industry and services" (excluding "public administration")
1995-2001	0.99	3.9	total labour costs	
1975/85/87- 2002	0.84-1.13	0.3 – 0.6[107]	wages & salaries	Bureau of Labour Cost Statistics Data (2002) - US Employment cost index: **quarterly index data,** not seasonally adjusted[108]
1985/87 - 2002	0.84-0.93	0.3 – 0.5[109]	total labour costs	

5.2. 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 3.2) be specified for the three cost streams: fuel, variable O&M and fixed O&M. There is little reason to believe that any of these correlations will be zero.

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

[106] Percentages (%) are "percentage points"; mean is arithmetic mean

[107] Highest standard deviation "Handlers, equipment cleaners, helpers, and labourers occupations";

[108] Considered groups are "Precision, production, craft, and repair occupations", "Handlers, equipment cleaners, helpers, and labourers occupations", "Public utilities" and "Electric, gas, and sanitary services". When analysing annual changes instead the sigmas increase, i.e. for "wages and salaries" new spread of sigma is 7.7% to 11.9% and for "total compensation" 0.7% to 1.0 %. If however, instead of quarterly data an average annual value is used the maximum sigma becomes 2.3% ("wages and salaries" for "Handlers, equipment cleaners, helpers, and labourers' occupations").

[109] Highest standard deviation "Electric, gas, and sanitary services";

standard deviations.[110] The assumed cross correlation coefficients are given in Table 5-3 and can be interpreted as follows.

It is assumed that for every pair of technologies *i* and *j* ($i \neq j$) the following correlations ρ_{ij} 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 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 $\rho_{ij} = 0.7$.
- The correlation coefficient between variable and fixed O&M is presumed to be low, and is set to 0.1.

Table 5-3 Assumed cross-correlations for the cost streams of existing generation assets

		Technology B		
Technology A		Fuel	Variable O&M	Fixed O&M
	Fuel	Table 4-2[111]	0	0
	Variable O&M	0	0.7	0.1
	Fixed O&M	0	0.1	0.7

5.3. *Results using the base case proxy risk estimates*

Figure 5-1 shows the portfolio results using the base case proxy risk estimates.[112] 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

[110] The results of a sensitivity analysis (see Appendix B) were encouraging in that the outcomes or the basic result did not change too much.

[111] This correlation is calculated on the basis of HPRs of historical fuel prices.

[112] Five risky technologies are considered, i.e. gas, coal, oil, nuclear and wind. More precisely, 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, i.e. ca. 2190 TWh [Electricity Information 2001]. Hydro is excluded from this mix.

O&M risk, the relative location of the EU-2000[113] and EU-2010[114] 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 4.

Further, the results indicate that, as before, it is possible to *costlessly* improve on the EU-2000 mix. 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.

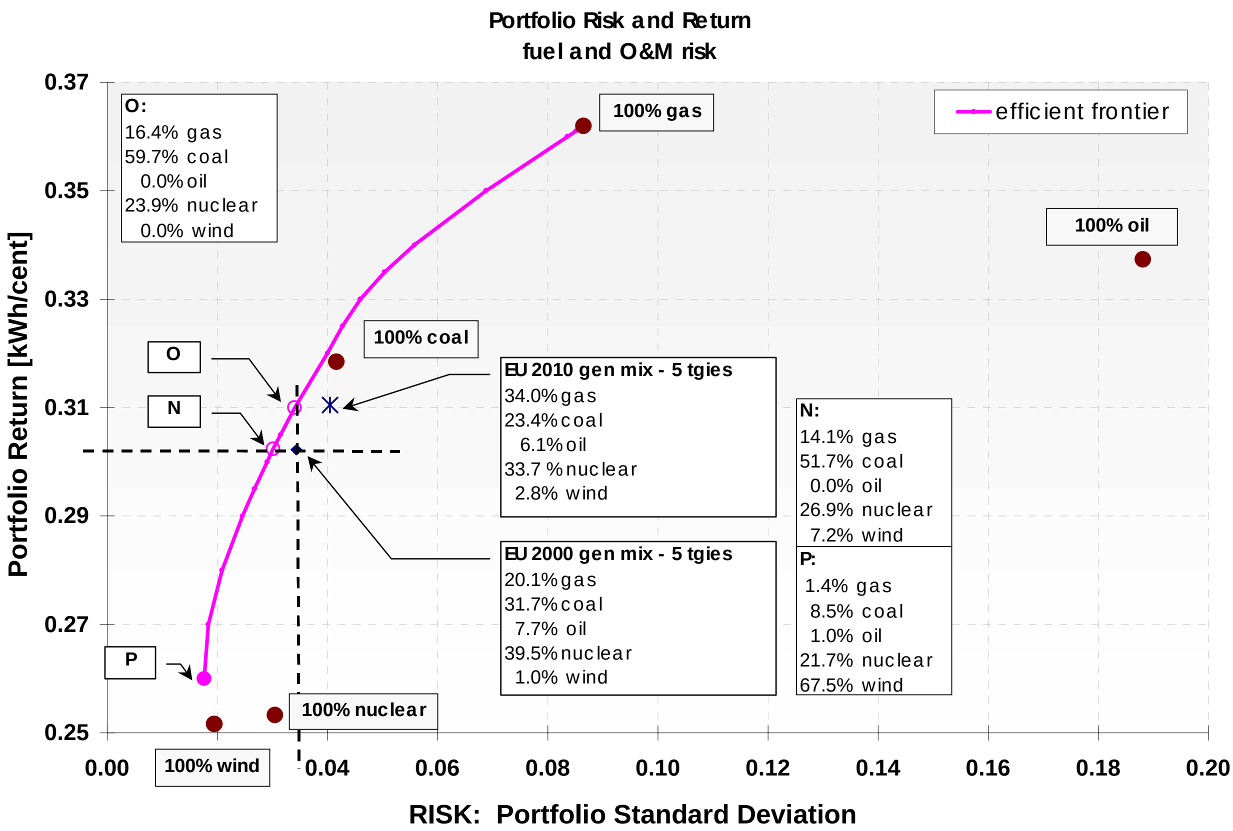

Figure 5-1 Portfolios of four conventional technologies – fuel and O&M risk[115]

[113] Contrary to the preceding sections the EU-2000 mix now contains wind. We have to include it because with the O&M risk wind becomes a risky asset like the four conventional technologies.

[114] Note that the EU-2010 mixes are based on higher generation level than the EU-2000 generation portfolio, i.e. ca. 2520 TWh vs. 2190 TWh.

[115] When comparing Figure 4-3 with Figure 5-1 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 87.

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 5-2 below.

Finally, Figure 5-2 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.

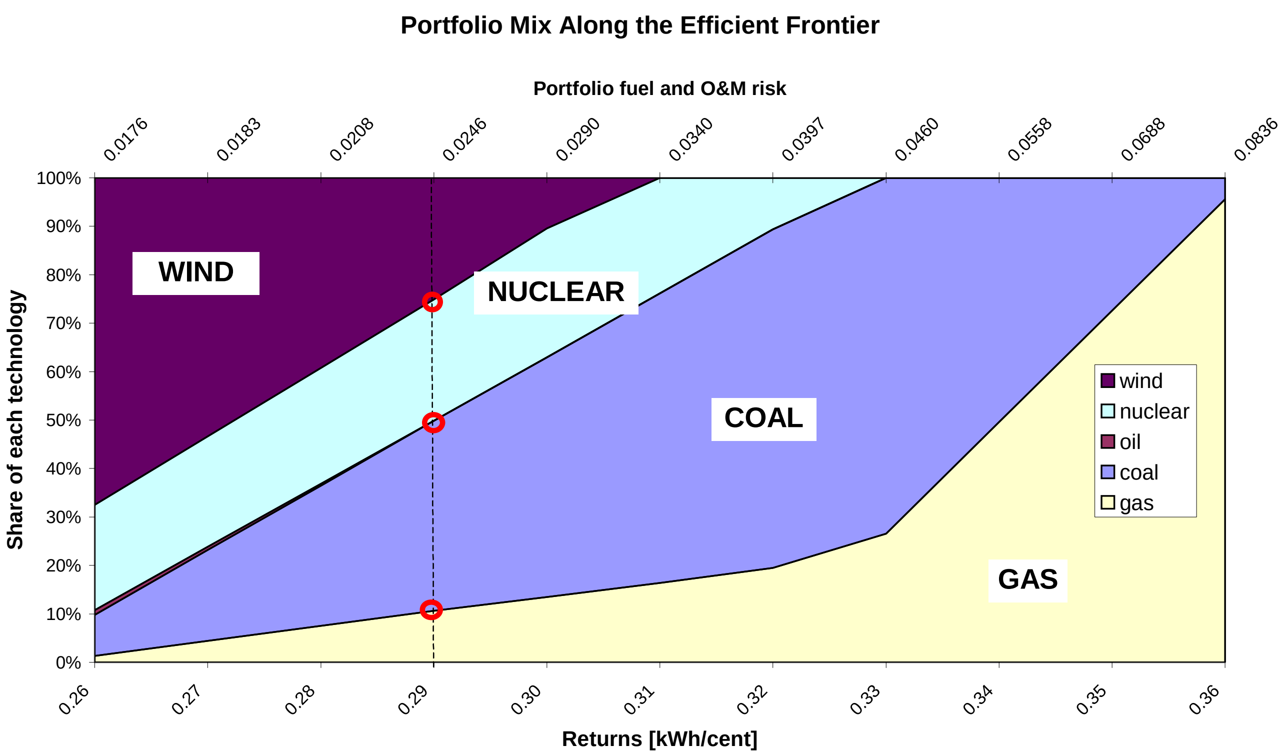

Figure 5-2 Portfolio mixes along the efficient frontier – fuel and O&M risk

5.4. Conclusion

To summarise, the following conclusions can be drawn from this section. When fuel and O&M cost risks are considered, the EU-2000 and the EU-2010 mixes are not efficient.

Improving them without changing their returns generally implies an increase in the share of coal and to some extent, wind.

This somewhat surprising result for coal is partly driven by the fact that this analysis considers neither external cost, nor existing taxes or subsidies. Moreover, it ignores differences between installed and new vintages of technologies. For example, most renewables have steeper learning curves than do conventional technologies [IEA 2000] and are therefore likely to experience more significant cost reductions in future. To the extent that the analysis of this section is based only on year 2000 costs, the importance of renewables in the portfolio is underestimated.

While the results to this section reflect only existing generation, the next section makes the important distinction between installed and additional capacity. This enables us to more realistically assess the EU-2010 mix. In evaluating such future mixes it is important to deal with new capacity additions and their attendant construction period risks and potential efficiency improvements. The next section examines such a more realistic portfolio consisting of new as well as existing technologies.

6. Case III: Optimal Portfolio Selection: Distinguishing between 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.[116] The 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 of new technologies may be overstated [Figure 6-5 and Figure 6-6]. This can be partly corrected by constraining existing capacity so it exactly equals its year-2000 share of the EU mix [e.g. see: Herbst (1990) p. 307]. We do this for the case of nuclear capacity, (Section 6.5) arguing that economics aside, it is unlikely that nuclear capacity will be decommissioned over the next 7-10 years. We compare this "politically 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 (see Appendix A).[117]

6.1. *Costs and Risks for Existing and New 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

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[116] 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.

[117] 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 and that wind generation in 2010 does not exceed the midterm potential for the EU [Huber et al. 2001].

generating capacity, as we did in previous sections, likely understates the share of renewables in the efficient mix.

Table 6-1 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.

Table 6-1 Levelised annual costs of technologies for CASE III

LEVELIZED COST cent / kWh	GAS		COAL		OIL[118]	NUCLEAR	WIND	
	CCGT	New Gas	Steam boiler	New Coal			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
Total busbar cost	**2.76**	**2.65**	**3.14**	**3.05**	**2.96**	**3.95**	**3.97**	**3.69**
Return (kWh/cent)	**0.362**	**0.378**	**0.318**	**0.328**	**0.337**	**0.253**	**0.252**	**0.271**

The levelised costs in Table 6-1 are taken from the IEA World Energy Outlook 2000 (WEO 2000).[119] WEO 2000 is a widely circulating and highly regarded source of current and future energy information.[120] Ideally, generating costs should be risk-adjusted. 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 (Appendix 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.

[118] These calculations are by the authors.

[119] In Appendix B we test the sensitivity of results with risk-adjusted costs based on Awerbuch (2002) as well as with wind costs from ElGREEN [Huber et al. 2001].

[120] Future costs are computed on the basis of WEO (2000) by means of interpolation.

6.2. Planning and Construction Period Risks and Cross-Correlations

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 $\sigma_{investment}$ to be approximately 20% (Table 5-1 page 58). 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 5-3 p. 60). For every pair of technologies *i* and *j* (*i ≠ j)* a cross correlation coefficient, ρ_{ij}, is assumed (Table 6-2). These are supposed to be quite small— 0.1. Next, as discussed in preceding sections, the correlation of investment costs for two different technologies is set to 0.7 (Table 6-2). Finally, the empirically derived cross-correlations estimates for the HPRs of fuel costs are given in Table 6-3.

Table 6-2 Assumed Cost Cross-correlation When Construction Period Risks are Included

	Technology B				
Technology A	Category	Construction Period	Fuel	Variable O&M	Fixed O&M
	Construction Period	0.7	0	0.1	0.1
	Fuel	0	Table 6-3[121]	0	0
	Variable O&M	0.1	0	0.7	0.1
	Fixed O&M	0.1	0	0.1	0.7

[121] This correlation is calculated on the basis of HPRs of historical fuel prices, see Section 2.5 and 3.

Table 6-3 Empirically Derived Fuel Cross-Correlations Estimates For Existing and New Vintage Technologies[122]

	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.

6.3. Base Case Results

Figure 6-1 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. Observe that the positioning of the EU-2000 and EU-2010 mixes relative to the efficient frontier and each other is almost unchanged.[123]

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[122] Since wind does not exhibit any fuel costs its correlation coefficient with the other technologies is zero and therefore not included.

[123] 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 but the EU-2000 mixes shown in the portfolio graph of this section refer to the generation level of EU-2010.

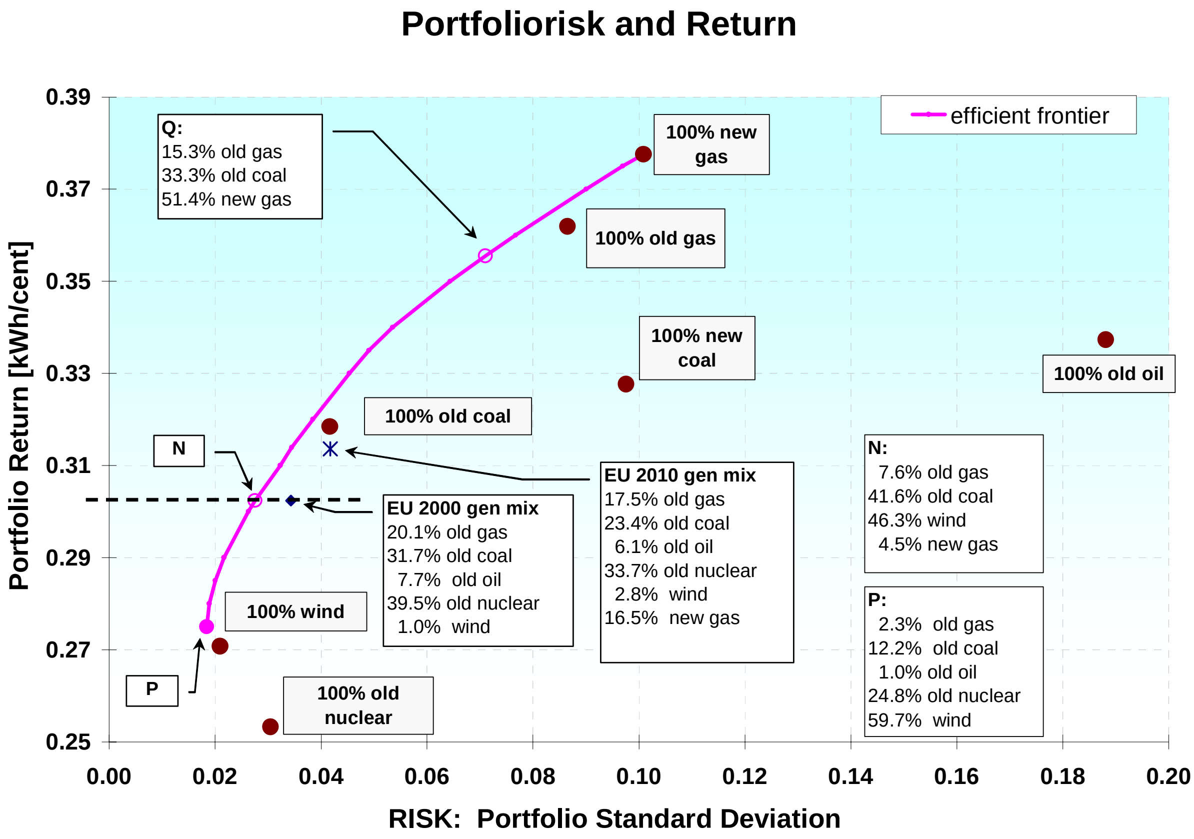

Figure 6-1 Base Case Efficient Portfolios: Fuel, O&M and Construction Period Risks for Existing and New Capacity[124]

As was the case in previous sections, Figure 6-1 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. 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.[125] Although not depicted here, such portfolios would contain added amounts of wind as discussed in subsequent sections.

Finally, Figure 6-2 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 6-1. Interestingly and somewhat surprisingly, the efficient frontier contains

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[124] Note that EU-2000 and EU-2010 are a mix of the four conventional technologies plus wind.

[125] Observe that while the 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 – in theory -be replaced entirely by a single technology— old coal.

no "new coal". This comes from the fact that "new coal" exhibits the highest investment period risk because its share of investment costs (see Table 6-1) 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 6-2).

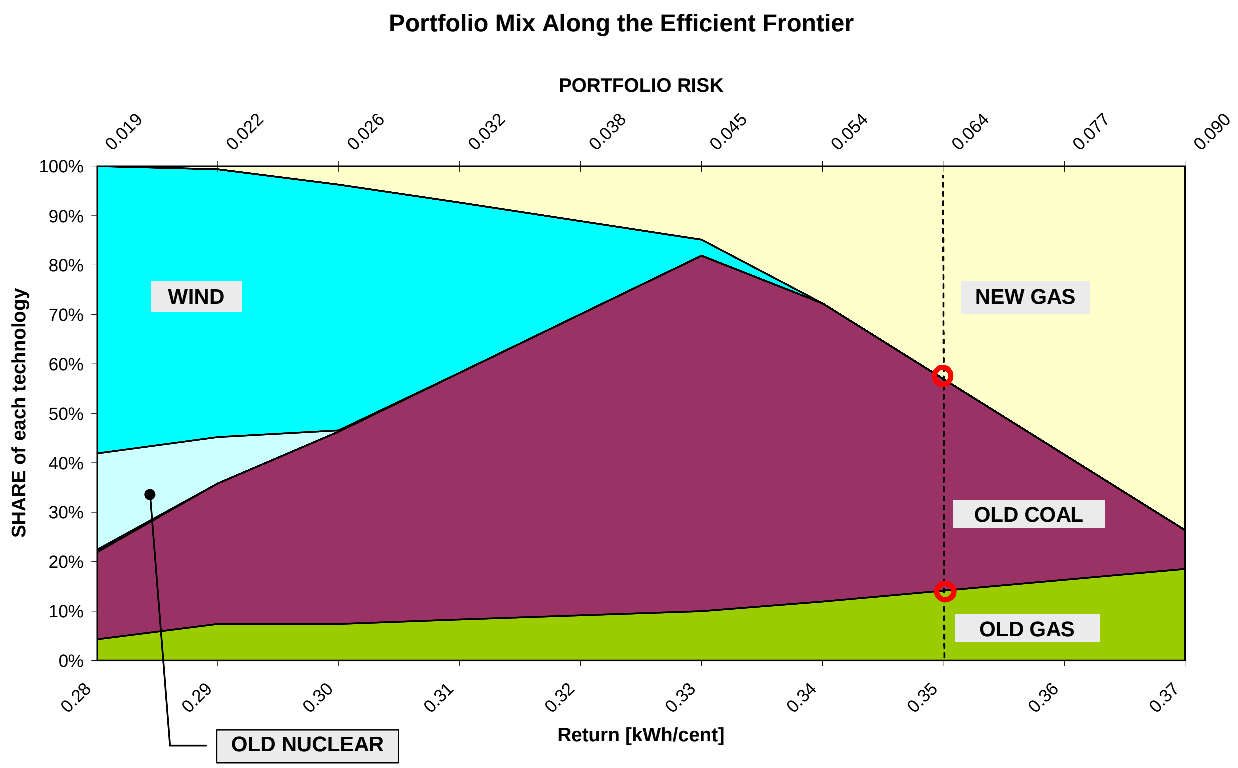

Figure 6-2 Portfolio mix along the efficient frontier- New and Old Capacity— Fuel, O&M and Investment Period Risks

6.4. 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 6-1, Figure 6-3). 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, indicating that better portfolios such as *U* (Figure 6-3) 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%"old coal" or of almost 60% wind in an EU 2010 mix is not feasible.

Feasible solutions can be obtained by, first, constraining the shares of existing technologies in the efficient frontier so that they cannot exceed their actual EU-2000 fraction. Therefore, for example "old coal" does not exceed a share of 27.5% in the mixes for 2010.

Second, the share of wind in the 2010 - mix must not exceed its technically feasible potential - according to Huber et al. (2001). Therefore the share of wind is constrained to 7.9% of the depicted EU-2010 mix.

This produces efficient solutions (Figure 6-3) 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 (8% vs. 3%), old gas (18% vs. 10%) and new gas (27% vs. 15%) as well as some more new coal (7% vs. 0%).

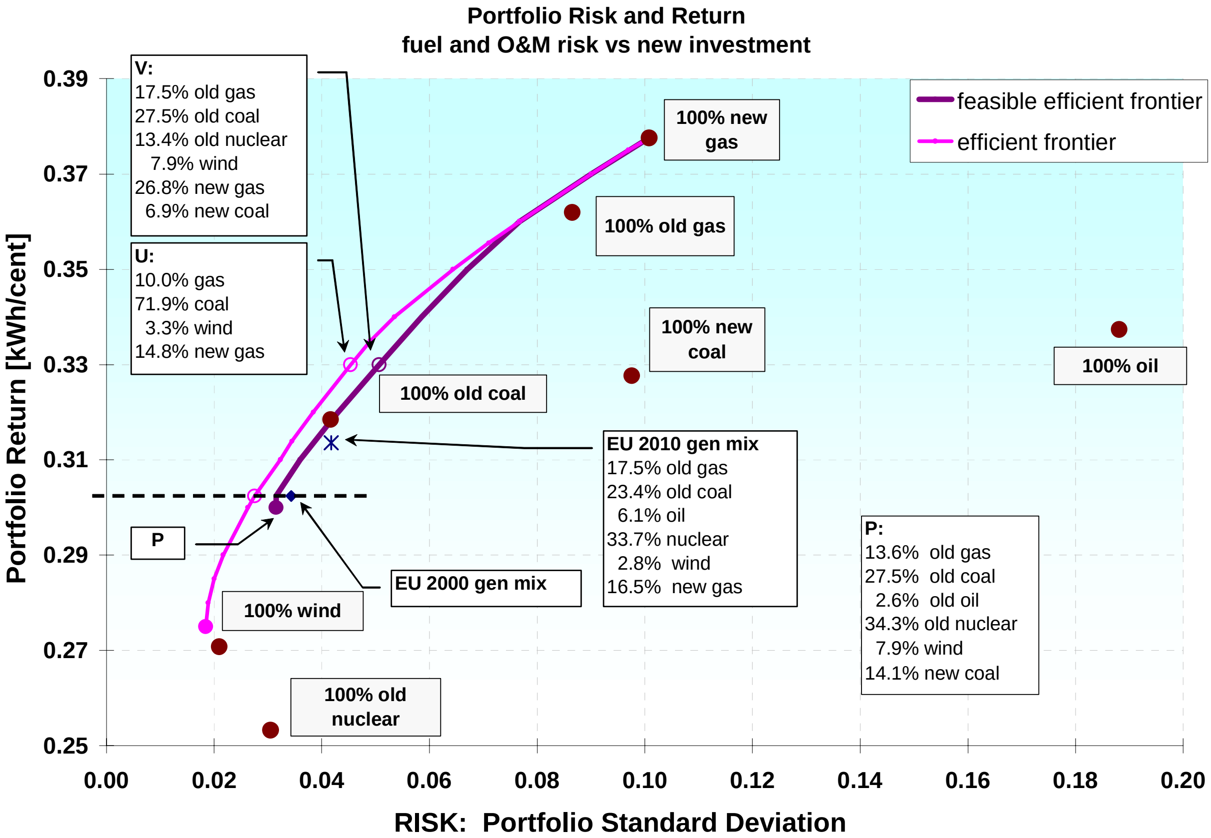

Figure 6-3 Efficient Feasible Portfolios: Fuel, O&M and Construction Period Risk for Existing and New Capacity[126]

Figure 6-4 shows the portfolio mix along the FEF. Since "old coal" is limited by its actual EU-2000 generation - corresponding to 27.5% in the 2010 mixes - and since wind is not allowed to exceed 7.9% other technologies replace "old coal" and wind at return levels where these limits are exceeded.

At point *U* (0.33 kWh/cent) coal attains its maximum share (71.9%) of the efficient frontier (see Figure 6-2). In the FEF the exceeding 44.4% "old coal" (71.9% minus 27.5%) are

[126] Note that EU-2000 and EU-2010 are a mix of the four conventional technologies plus wind.

replaced primarily by new gas, old nuclear, new coal and old gas. Note that new coal is a new entrant to the FEF and attains a maximum share of 14%.

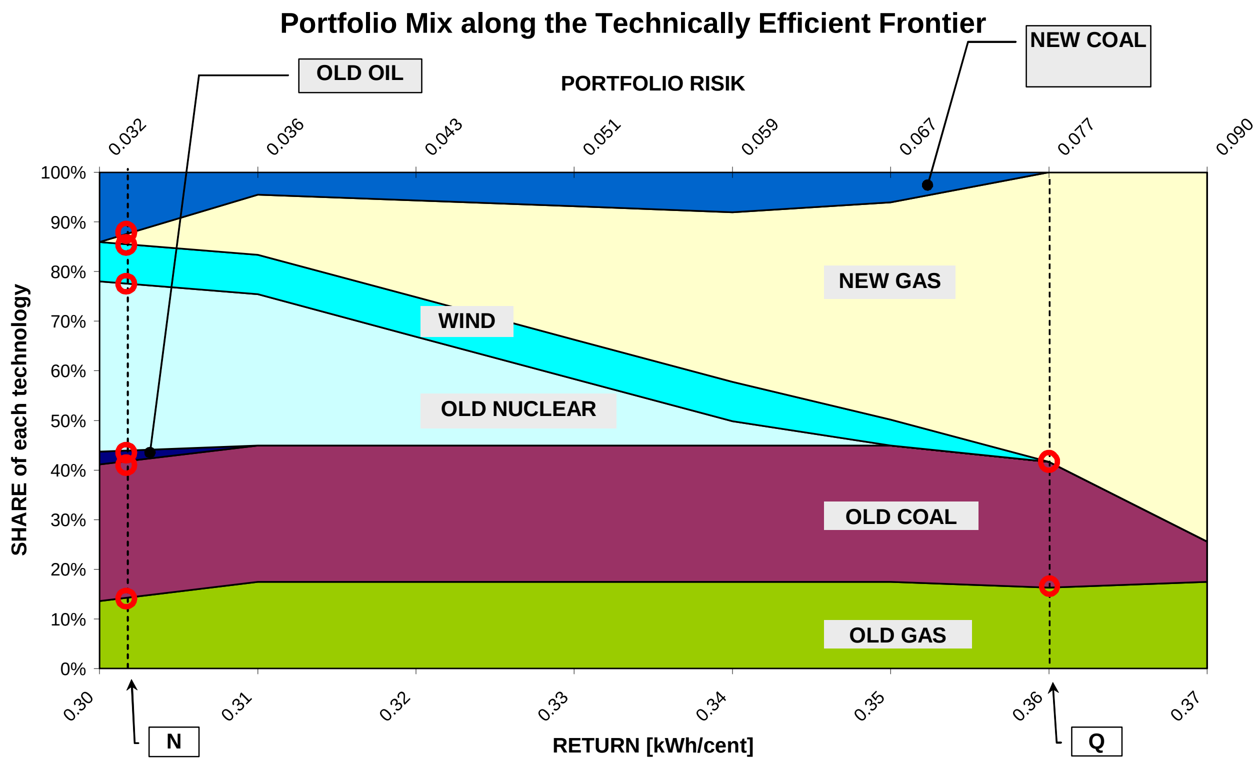

Figure 6-4 Portfolio Mix Along The Feasible Efficient Frontier – Fuel, O&M Construction Period Risk

6.5. The Effect of Political Constraints on the Efficient Solutions

The feasible efficient portfolios presented in the last section contain 0% nuclear at returns in excess of 0.35 kWh/cent, see Figure 6-4.

A 0% nuclear share is obviously not a politically or practically feasible solution for any 2010 portfolio, since it is highly unlikely 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 "politically feasible".

However, politically efficient portfolios can be *approximated* by constraining nuclear generation to its actual generation level[127] so that it maintains its 34.3% share over all 2010 mixes. This produces solutions that are more politically feasible with respect to nuclear capacity. These solutions lie along what we call the *politically efficient frontier* (PEF).

[127] 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. The PEF clearly moves to the right, so that it just about passes through the projected EU-2010 mix, as might be expected. Points *V* on the FEF produce the same return as *W,* on the PEF, but W exhibits 15% more market risk. This is one measure of the economic cost associated with the political constraints. Compared to portfolio *V*, *W* contains significantly less old coal (4.1% vs. 27.5%), more nuclear (34.3% vs. 13.4%), more new gas (45.5% vs. 26.8%) and no wind.

Second, constraining nuclear as we did severely reduces the maximum portfolio return levels compared to the technically feasible solution (Figure 6-5). 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 6-5). This is another measure of the cost of the political constraint. Observe that point *E* consists of 34.3% nuclear and 65.7% new gas.[128]

[128] 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 politically feasible. However, we did not exclude these solutions from the politically efficient mixes a priori.

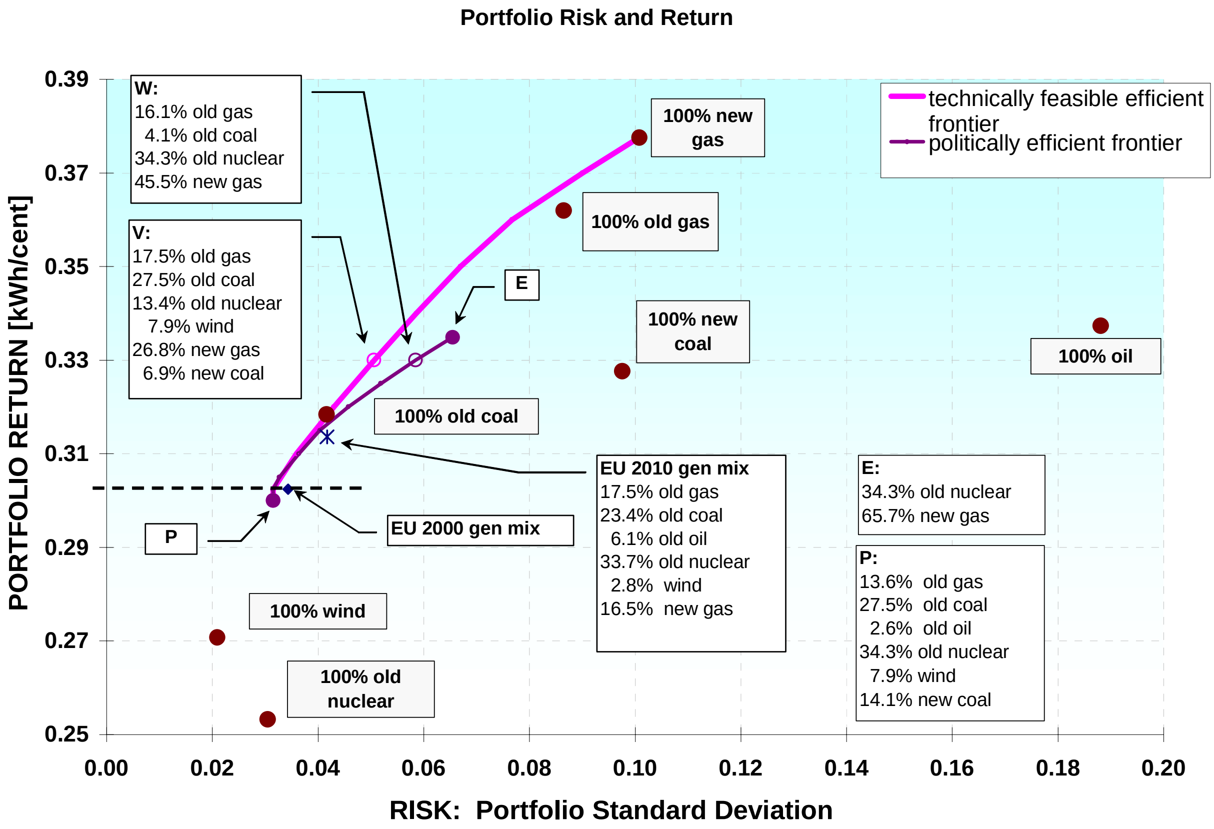

Figure 6-5 Efficient Politically Feasible Portfolios: Fuel, O&M and Construction Period Risk for Existing and New Capacity[129]

Figure 6-6 shows the portfolio mix along the PEF. Since nuclear is constrained to its actual generation its share rests constant over the whole PEF. At higher return levels, this is mainly at the expense of wind but also of old and new coal.

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, the politically efficient solution would contain - similar to the FEF - 17.5% old gas, 27.5% old coal, 1.4 old oil, 34.3% nuclear, 7.9% wind, 2.4% new gas and 9.0% new coal.

[129] Note that EU-2000 and EU-2010 are a mix of the four conventional technologies plus wind.

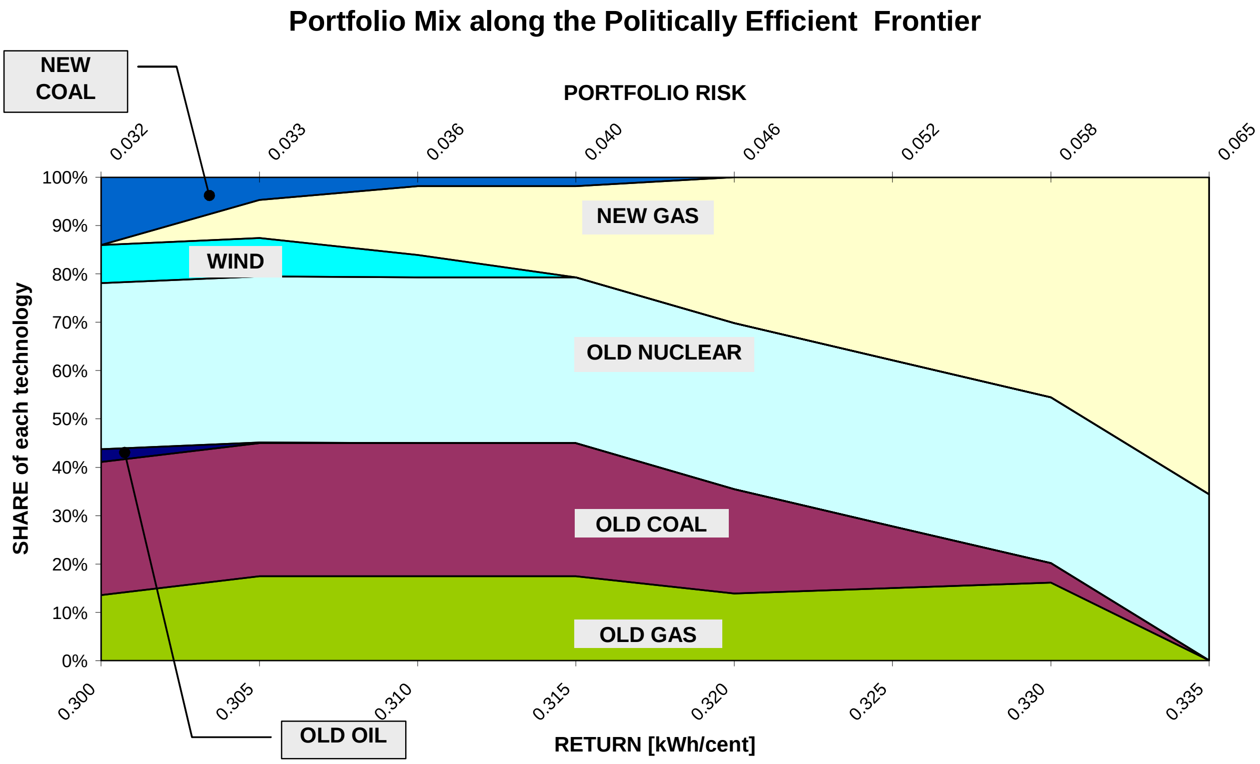

Figure 6-6 Portfolio Mix Along The Politically Efficient Frontier – Fuel, O&M Construction Period Risk

6.6. Conclusion

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 politically feasible results presented here.

However, while decommissioning costs are not explicitly included, we have approximated the equivalent politically 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 politically efficient solutions that illustrate the economic costs of political policies.

7. Summary of preliminary 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 defined a more subtle, and, we believe, more important 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.[130]

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.

In general, our results clearly indicate – with the underlying assumptions and simplifications specified in Appendix A - 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 and similar fixed-cost technologies.

More specifically, the results suggest that increasing the share of wind in the generating mix up to its mid-term potential for 2010, i.e. 7.9%, does not increase overall portfolio generating costs as compared to the year-2000 EU mix. Under some circumstances, additional portfolio shares of fixed cost renewables even serve to *reduce* overall cost and risk. This result, which holds under of the specified assumed conditions, runs contrary to most analyses and to widely

[130] 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.

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 does not increase overall cost and risk— changes little.

Finally, we model the effect of political constraints on the optimal solution. We do this by constraining certain technologies, in this case nuclear, to their Year-2000 share of total generation under the assumption that nuclear capacity will not be decommissioned over the next 7-10 years. This produces a politically efficient frontier (PEF) and a set of politically efficient solutions. While these are generally quite inferior to the technically feasible solutions produced previously, they can still be improved with the addition of wind.

8. 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 – given the underlying assumptions and simplifications specified in Appendix A - sub optimal 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 strongly suggest that renewables and other fixed cost technologies 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.

We began our analysis 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.[131] 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.

8.1. Evaluating the Year-2000 EU Portfolio

We next introduce models that reflect the risk of fuel as well as the risk associated with fixed and variable O&M. This allows us to more realistically evaluate the current year-2000 portfolio. Specifying O&M risk requires us to also specify the cross-correlation coefficients between wind and the conventional technologies. 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.[132] Because technology choices and trade-offs along the efficient frontier are now somewhat more difficult to interpret, we introduce special graphs (such as Figure 5-2) that depict the efficient possibilities more clearly.

The additional O&M risk that is now included serves to increase the overall standard deviations. However, this increase affects wind as well as the conventional technologies so

[131] Recall that Equation 3.2, which is the expression for portfolio risk, reduces to a straight line when one of the variances (e.g. σ_1^2) is set to zero. Portfolio return is also a linear function of the portfolio shares and their returns.

[132] 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.

that the principal message remains largely unchanged: adding wind to the year-2000 and the projected year 2010 mixes will serve to reduce cost and risk.

We estimate the standard deviations for the fixed and variable O&M costs 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. We use financial proxies because we do not have access to appropriate historic O&M cost data. Under the approach, we assume that 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.

8.2. Evaluating Projected EU Generating Mixes

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.[133] In order to more fully evaluate the projected 2010 EU generating mix, we transition to a more complex model that includes planning and construction period risks in addition to the fuel and O&M risks included in the previous analyses. This enhanced model allows us to distinguish 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 assumed to be 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 allowing us to distinguish 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. In addition, it enables us to constrain the share of existing technologies to their year 2000 share and to limit wind generation to its 2010 mid-term potential [Huber et al 2001], so that the solutions are *technically feasible*.

The enhanced model allows us to examine the effect of political constraints on the optimal solutions by developing what we term *politically feasible 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. We model this political effect and produce a set of politically efficient solutions by constraining nuclear capacity to its share in the EU-2000 mix. This enables us to compare the politically feasible

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[133] 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 capacity installed. The presented model does not deal with installed capacity but with electricity generated and therefore implies *average* full load hours.

efficient solutions to unconstrained or technically efficient solutions. Constraining the nuclear share 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 wind. 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. Since environmental and other externality benefits of renewables are not considered, this result suggests that the addition of renewables to the mix is highly desirable.

As a corollary, we observe that current national policies that focus on gas expansion to the exclusion of renewables (at least in the US and perhaps elsewhere) are inappropriate. In some instances such policies will only serve to increase risk disproportionately to any attained cost reductions. Gas expansion cannot be implemented in an economically efficient manner without a simultaneous national focus on reducing the cost of PV, wind and other riskless renewables. Such cost reductions could be accomplished through various policies including, a national portfolio standard to accelerate PV production.[134]

The basic finding of this analysis therefore seems quite robust, and does not materially change even when the parameter estimates are changed significantly in the sensitivity analysis.

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[134] For a discussion of market transformation policies see: Duke and Kammen (1999).

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Appendix A. Assumptions and Limits Affecting the Analysis of Generation 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]."[135]

   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 (see also Section 2.5).

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]." Helfat (1988) states that the simple normality assumption is sufficient to enable the portfolio choices of expected utility maximisers to be analysed in terms of mean and variance. Yet, she applies this method to symmetrical distributions that are not necessarily normal.

   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,*[136] [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

[135] See also Herbst (1990) p. 303.

[136] *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.

plant) is constructed. Technology choice may further affect asset value to the extent that grid connection, siting and similar costs may differ for different technologies.

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.[137] 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

[137] This is underpinned by e.g. Ibbotson Associates (1998) p. 27.

out there that cannot and have not been reflected by our historic SD estimates,[138] and which may someday rear their (ugly?) heads. We however, choose to focus on that which is probabilistically tractable (see also Section 2.6).

6. **Expected returns:** Expected returns are based on traditionally estimated levelised generation costs taken from WEO (2000).[139] 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.

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[138] 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]

[139] A sensitivity analysis is performed in Appendix B using risk-adjusted costs developed in Awerbuch (2002).

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.[140]

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 politically feasible portfolios* may therefore be systematically overstated, (see Figure 6-3 and Figure 6-4). One simple remedy for this problem would be to specify additional constraints that hold existing assets at their current portfolio share, less projected retirements. [Herbst (1990) p. 307]. We have not so constrained the model in the interest of finding a range of optimal mixes.

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[141] and supply data from ESA (2000). For the final 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 Section 5.1, we used financial proxies to derive estimates for all but the fuel-price risk. We had no access to historic project data covering

[140] 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.

[141] Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

O&M costs.[142] 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.

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 in Appendix B.

10. **Electricity Grid:** We assume that each technology can - independent of its location and type - feed into the electricity grid. Moreover, we do not consider any transmission constraints within the grid.

11. **"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 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)].

[142] 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.

Appendix B. Sensitivity analysis

Sensitivity analysis was performed for the base-case and technically feasible portfolios of Section 6, which include existing as well as new capacity. The analysis comprised a

(1) Variation of cost stream risk, i.e. their HPR standard deviations (SD) – (see Section 6),

(2) Variation of their cross-correlations (see Table 6-2 p. 66); In addition, an analysis is performed with

(3) Risk-adjusted costs and with

(4) Higher wind costs from Huber et al. (2001)

The resulting efficient frontiers were compared to the ones obtained in Section 6.

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 5-2) 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 on 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.

Section 5.1 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 5-1 p. 58). 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 5-1). The base case and sensitivity values for these SDs are given in Table B-1.

Table B-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 B-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 B-2).

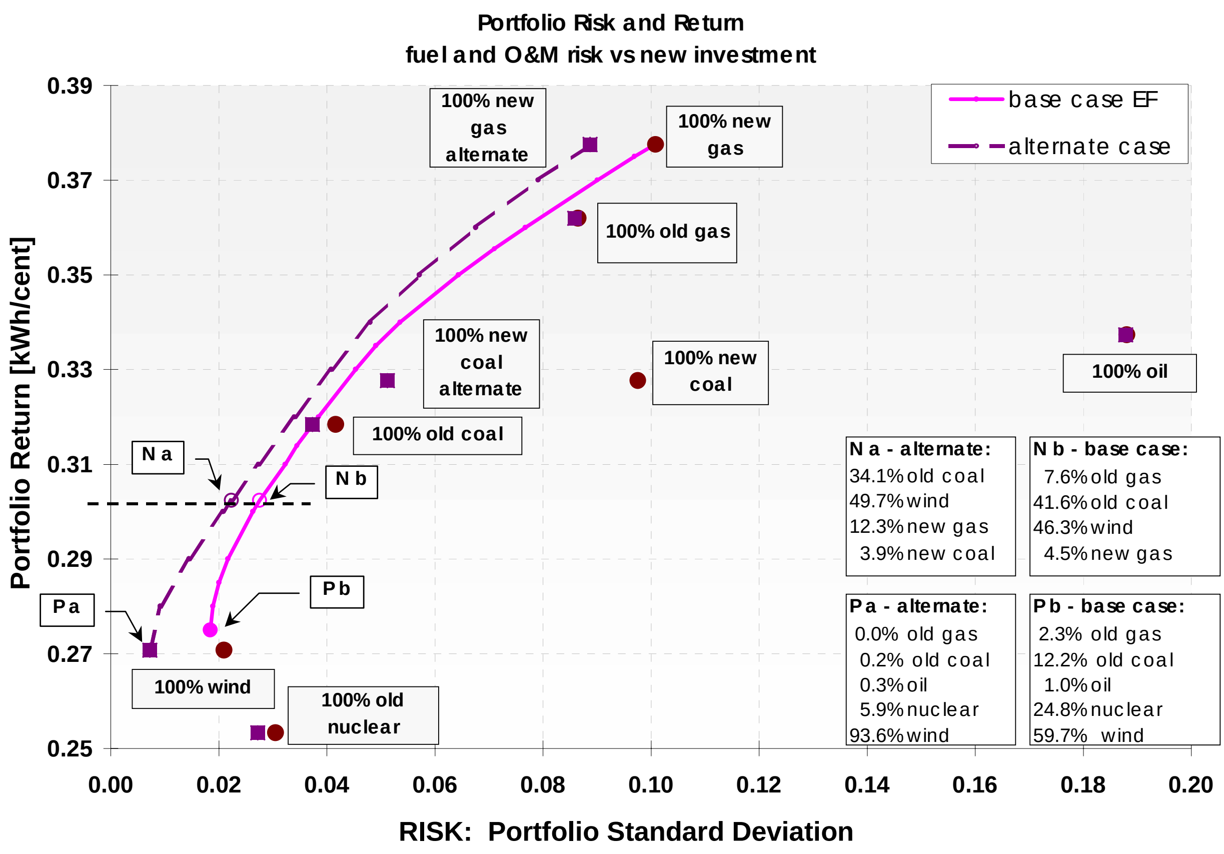

Figure B-1 Sensitivity analysis: The Effect of lower Cost SDs on the Efficient Frontier

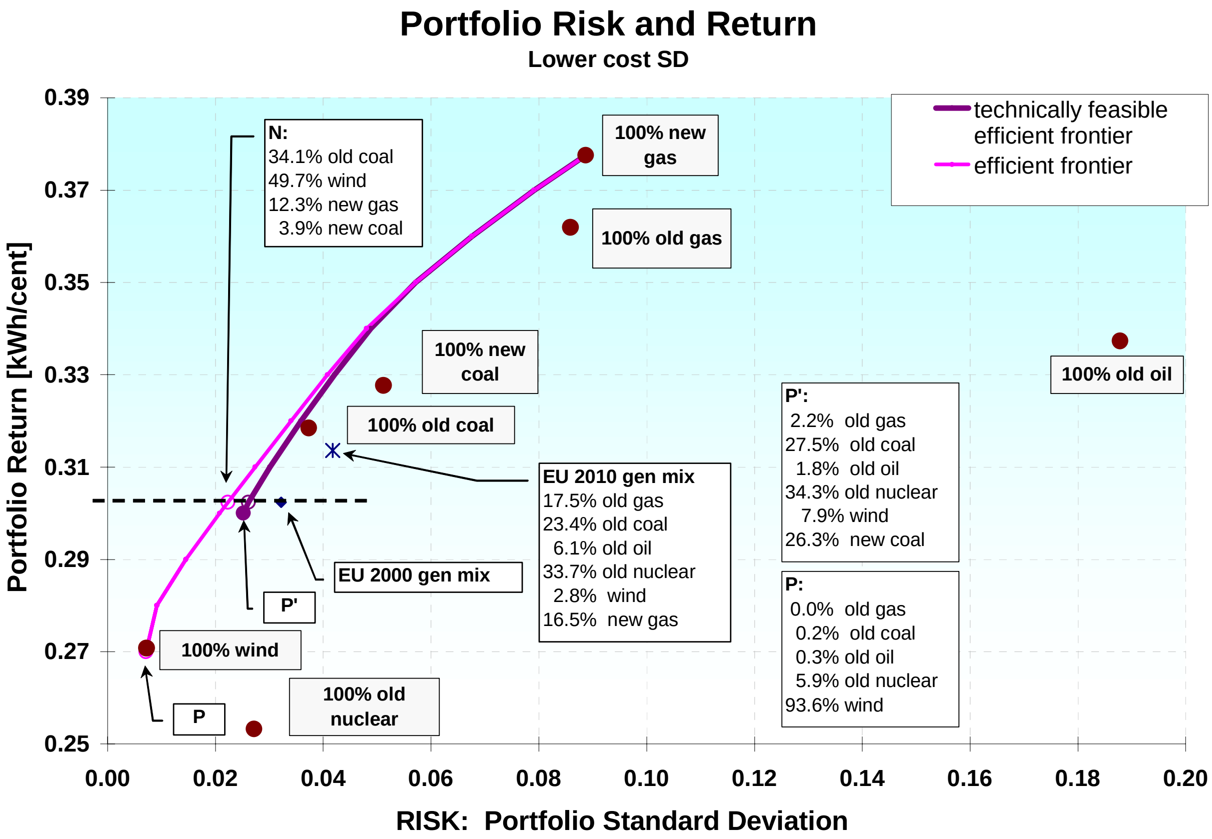

Figure B-2 Sensitivity analysis: The Effect of lower Cost SDs on the Efficient Frontier and the Technically Efficient Frontier

Figure B-2 shows that, like the base case results, (Section 6), the new efficient frontier (EF) is significantly different to the new FEF (*feasible efficient frontier*). The maximum deviation between the two frontiers occurs at a return of 0.30 kWh/cent where the risk of the new FEF is 0.025 as compared to 0.021 for the new EF (Table B-2).

Table B-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				
0.2800	0.0189	0.0092	-51.5%			
0.2900	0.0217	0.0145	-33.2%			
0.3000	0.0263	0.0208	-20.9%	0.0315	0.0252	-20.2%
0.3100	0.0320	0.0273	-14.5%	0.0359	0.0301	-16.3%
0.3200	0.0385	0.0340	-11.5%	0.0430	0.0359	-16.6%
0.3300	0.0453	0.0408	-10.0%	0.0506	0.0421	-16.9%
0.3400	0.0535	0.0480	-10.3%	0.0586	0.0489	-16.6%
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 B-3, which indicates some changes in the efficient mixes compared to the base case EF (Figure 6-2). 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.[143] 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 B-3 and Figure B-4 enable us to compare the technology makeup of the new EF (Figure B-3) relative to the new FEF (Figure B-4). The differences are very close to the ones for the base-case EF and FEF.

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[143] The reason why "old gas" is no longer included in the efficient frontier is that decommissioning costs are not considered so that this 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 Appendix A).

Content of Base Case FEF vs. New FEF

The differences between the content of the base case FEF (Figure 6-4) and the new FEF (Figure B-4) are the following. First, there is significantly more "new coal" in the new FEF. Second, “old gas” is almost not included in the new frontier. However, in both cases the share of wind corresponds to the maximal feasible fraction of 7.9% up to return levels of 0.33 kWh/cent.

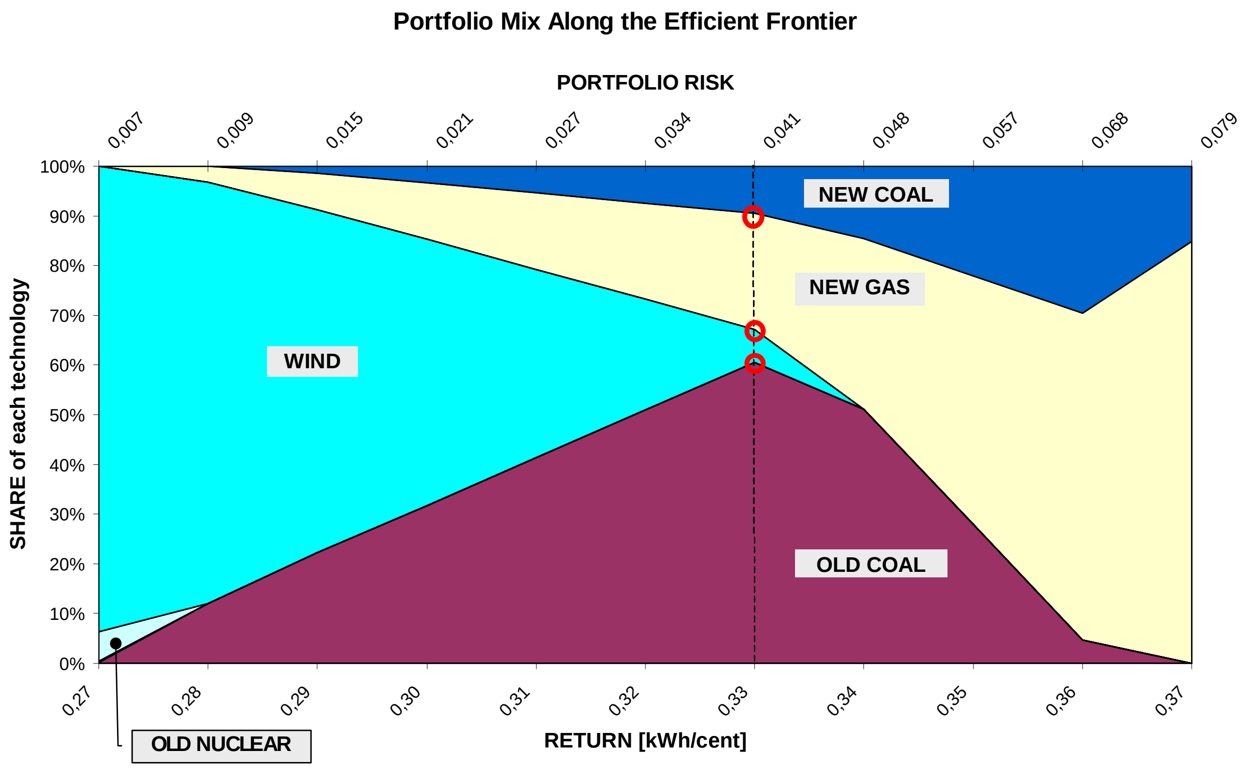

Figure B-3 Sensitivity analysis of the portfolio mix along the efficient frontier using different SD of cost streams

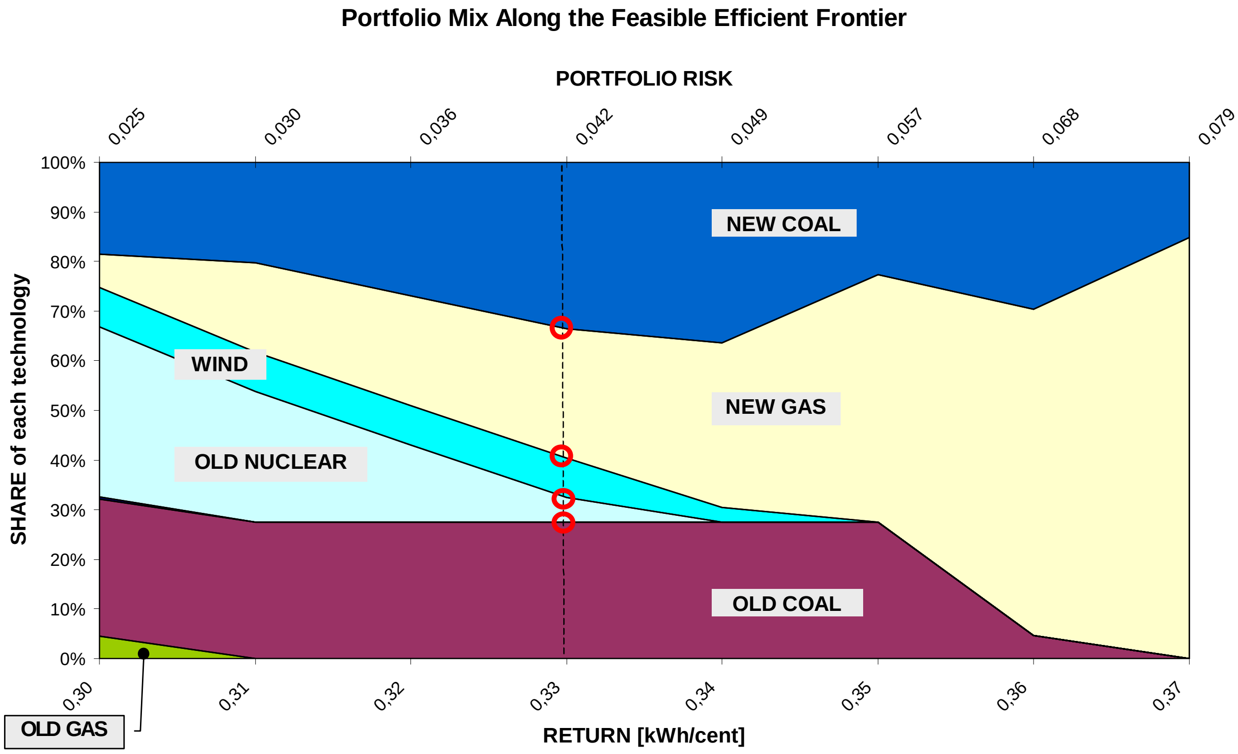

Figure B-4: Sensitivity analysis of the portfolio mix along the technically feasible frontier using different SD of cost streams

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, up to return levels of 0.33 kWh/cent wind maintains its maximal feasible share of 7.9% in both cases. However, if its 2010-mid-term potential were higher the new FEF would contain more important shares of wind than in the base case. 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 on 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 significantly. In the case of the FEF the fraction of wind stays at its maximal feasible share of 7.9%.

With these variabilities set back to their base case levels (Section 6.2), 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. The remaining coefficients were left unchanged. Table B-3 shows the base case values from Table 6-2 (shown in parentheses) as well as the sensitivity values.

Table B-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) / **0.1**	(0) / 0	(0.1) / 0.1	(0.1) / 0.1
	Fuel	(0) / 0	Table 6-3[144]	(0) / 0	(0)/ 0
	Variable O&M	(0.1) / 0.1	(0) / 0	(0.7) / **0.1**	(0.1) / 0.1
	Fixed O&M	(0.1) / 0.1	(0) / 0	(0.1) / 0.1	(0.7) / **0.1**

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 6-1) - 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 B-4 gives the risk for various return levels, starting with *P* – the lowest possible return of the efficient frontiers.

Table B-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%

[144] This correlation is calculated on the basis of historical fuel prices.

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/ cent. As compared to the base case (Figure 6-2) “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 of Section 6. Since the efficient frontier is not altered significantly, we did not estimate a revised FEF.

B.3. Sensitivity analysis with risk-adjusted costs

In financial portfolios, equity share prices represent the risk-adjusted present value of all future cash flows.[145] Consistent with this, the efficient frontier is now estimated using risk-adjusted technology costs. Table B-5 gives the calculated costs, which are based on Awerbuch (2002).

Table B-5 Risk adjusted costs[146]

ANNUAL COST cent / 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
Total busbar cost	**5.00**	**4.79**	**4.58**	**4.45**	**5.37**	**5.65**	**4.24**	**3.94**
Return (kWh/cent)	**0.200**	**0.209**	**0.218**	**0.225**	**0.186**	**0.177**	**0.236**	**0.254**

The resulting efficient frontier (Figure B-5) has a significantly different shape than the base case Figure 6-1. It covers different return levels than the base case, i.e. it ranges from 0.177 to 0.254 kWh/cent, and is much steeper than the base case frontier. The EU-2000 and EU-2010 mixes are far from being efficient and there do not exist portfolios with the same risk as EU 2000 and 2010.

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[145] For details see e.g. Brealey and Myers (1991) p. 13-14.

[146] Based on Awerbuch (2002)

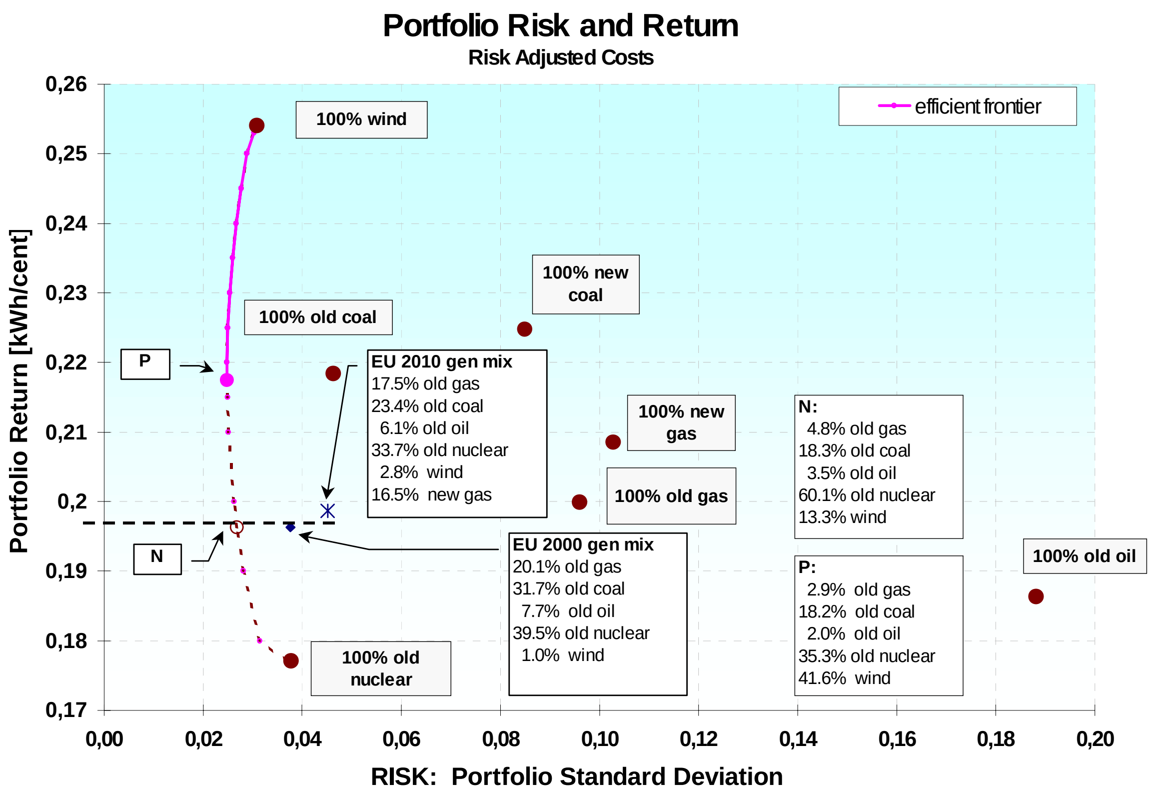

Figure B-5 Sensitivity analysis: The Effect of Risk-Adjusted Costs on Efficient Portfolios[147]

The efficient frontier (Figure B-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.

[147] Note that EU-2000 and EU-2010 are a mix of the four conventional technologies plus wind.

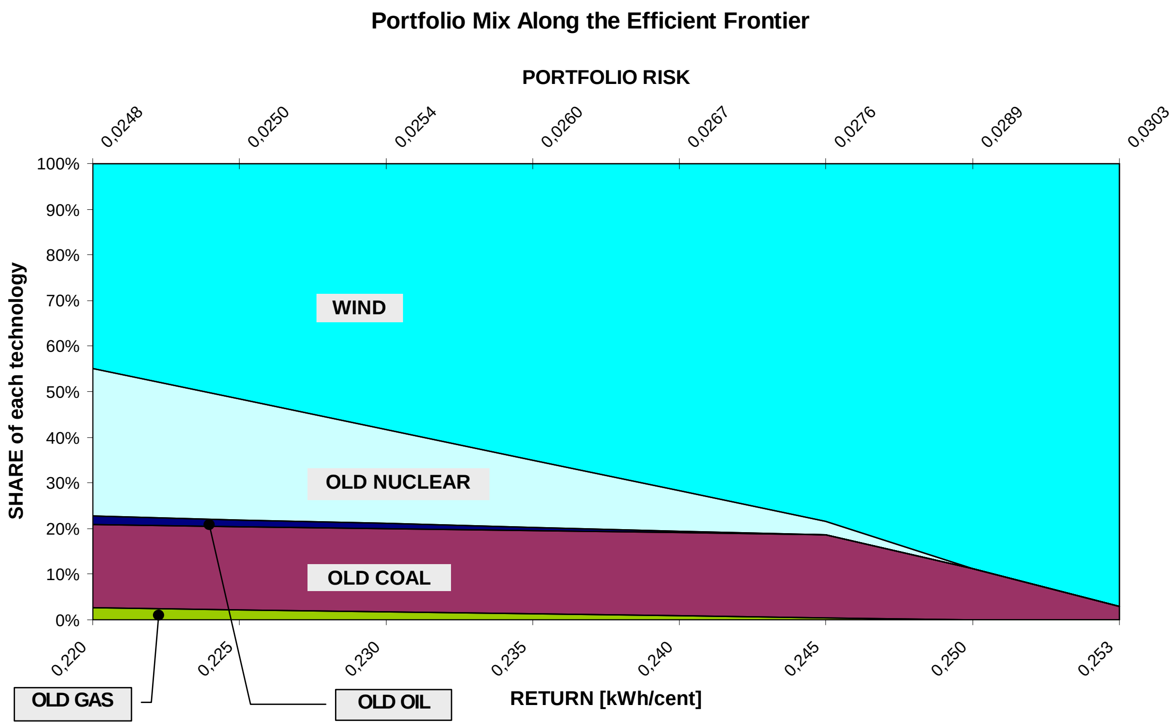

Figure B-6 Sensitivity analysis of the portfolio mix along the efficient frontier using risk-adjusted costs

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".[148]

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.

B.4. Sensitivity analysis with higher wind costs

In this part of the sensitivity analysis we use wind costs from ElGREEN [Huber et al. 2001] instead of the WEO (2000) costs. As shown in Table B-6 the ElGREEN total busbar costs are more than 70% higher than the WEO (2000) costs - i.e. ElGREEN wind return is significantly lower.

When comparing the base case politically feasible frontier (PEF) of Figure 6-5 with the new PEF in Figure B-7 the following differences appear. First, the return of 100% wind is below 0.25 kWh/cent and can therefore not be displayed on the graph. Second, the new PEF starts at lower return levels than the old one (P' is lower than P). Third, at return levels below 0.32 kWh/cent the two PEFs deviate significantly while at higher return levels they are almost identical.

[148] This is of course not a technically feasible solution since the fraction of wind exceeds its year 2010 mid-term potential.

Note that EU-2000 and EU-2010 are only displayed once - based on WEO costs - because using ElGREEN wind costs does not distinctly lower their returns since the fraction of wind is quite low in both cases.

While the content of *N* and *N'* - the portfolios that exhibit the same return as EU-2000 - only differs as for the fraction of wind, i.e. *N* 7.9% vs *N'* 3.4% wind generation, *N'* bears approx. 10% more risk than *N*.

The portfolio mixes along the new PEF do not differ significantly from the base case PEF in Figure 6-6 and are therefore not displayed. In contrast to the base case PEF there is some more new coal up to return levels of 0.31 kWh/cent and less wind. At mixes with higher returns than 0.31 kWh/cent there is 0% wind in the new PEF.

Table B-6 Costs of Wind - WEO 2000 versus ElGREEN[149]

ANNUAL COST cent / kWh	WIND	
	WEO 2000 new	ElGREEN
Fixed investment	2,80	4,99
Fuel	0,00	0,00
Variable O&M	0,00	0,00
Fixed O&M	0,89	1,41
Total busbar cost	3,69	6,40
Return (kWh/cent)	0,271	0,156

[149] For the annual ElGREEN wind costs specific investment costs of 950 €/kW were selected. The interest rate was set to 6.5%, life time to 15 years and the annual variable O&M to 3% of the specific investment costs. For the full load hours we chose 2024 hours/year. That corresponds to the average full load hours for the EU [Huber et al. 2001].

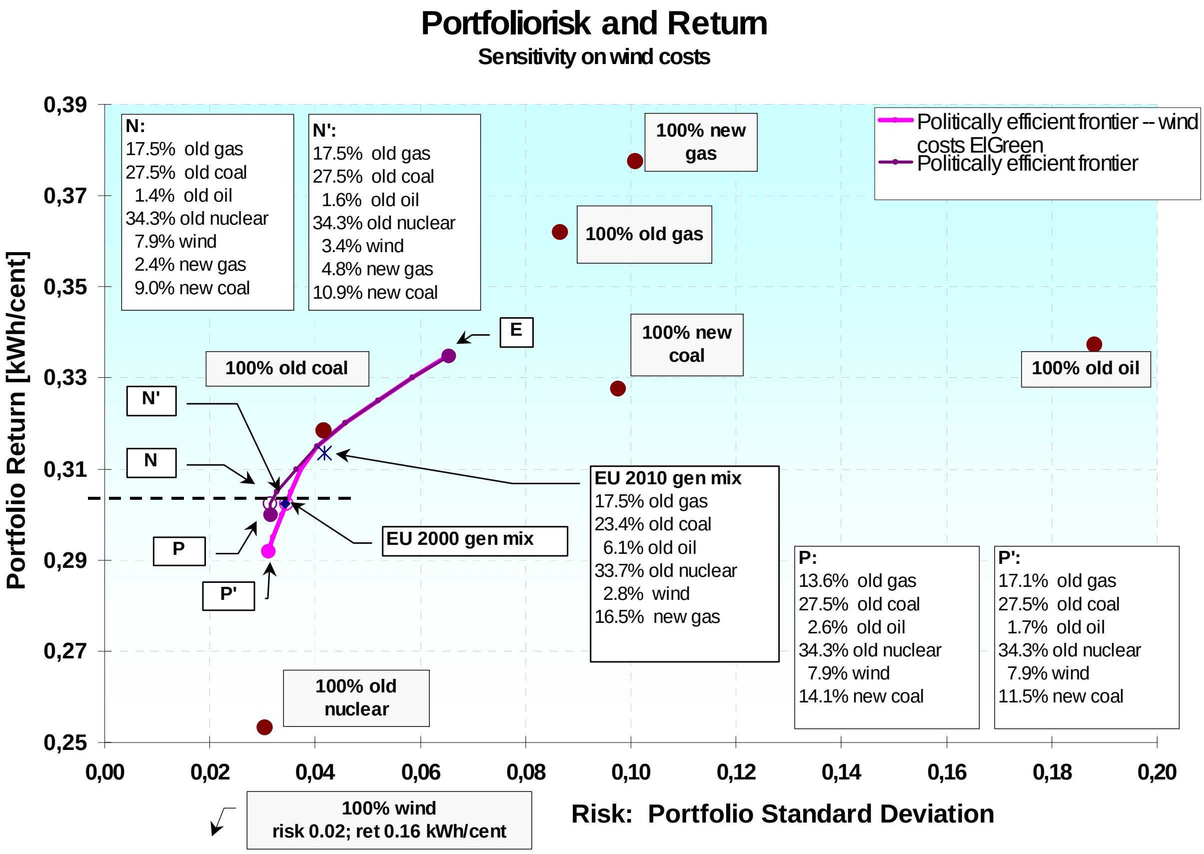

Figure B-7 Sensitivity analysis: The Effect of Higher Wind Costs on the Politically Efficient Portfolios[150]

As a conclusion, using higher costs for wind the EU-2000 mix comes to lie on the PEF and turns out to be efficient - in contrast to the EU-2010 portfolio. The new PEF contains less wind because wind is approx. 70% more expensive.

However, the results of this section have to be interpreted with some care because the costs of technologies (Table B-6 and Table 6-1) come from two different studies with different underlying assumptions. It would be preferable to compare two complete sets of costs (like in section B.3) in order to produce more realistic results.

[150] Note that EU-2000 and EU-2010 are a mix of the four conventional technologies plus wind.