Portfolio-Based Electricity Generation Planning: Implications for Renewables and Energy Security

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Abstract

Traditional electricity planning processes focus on finding the *least-cost* generating alternative. Given today's dynamic and uncertain environment however it is impossible to correctly identify the 30-year "least cost" option, assuming such an option exists. Energy planning represents an investment-decision problem and investors commonly apply portfolio theory to manage risk and maximize portfolio performance under a variety of unpredictable economic outcomes. Energy planning techniques need to focus less on trying to identify the least-cost alternative and more on developing optimal generating portfolios that minimize cost for given levels of risk. This means abandoning traditional *stand-alone* kWh generating costs measures and instead evaluating conventional and renewable energy sources on the basis of their *portfolio cost*— their cost contribution relative to their risk contribution to a portfolio of generating assets. 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 security generally focuses on the threat of abrupt supply disruptions. This paper suggests that it has a more profound aspect: mitigating fossil price volatility. An extensive body of research indicates that fossil volatility significantly disrupts the economies of consuming nations, potentially exacting hundreds of billions of dollars from the US and EU economies alone. Fossil risk may be even costlier in developing nations that import higher shares of their fossil needs and are subject to additional currency fluctuations. Energy security is reduced when countries hold inefficient portfolios that are needlessly exposed to fossil and other price risks.

This non-technical paper describes the underlying portfolio-theory ideas and illustrates how electricity-generating mixes can benefit from additional shares of wind, geothermal and other renewables. Compared to existing, fossil-dominated mixes, *efficient* portfolios reduce generating cost while including greater renewables shares in the mix thereby enhancing energy security. For example, the projected Mexico Year-2010 mix consists of 75% fossil generation with an overall cost of 5 US-cents/kWh. By comparison, optimized portfolios for Mexico reduce cost by almost one-third (to 3.6 cents/kWh), while lowering the fossil share to 60% of the mix and increasing wind generation from 0% to 9% and geothermal to 11%. This increase comes in spite of wind's higher 5.1-cent stand-alone cost, 2.0 cents more than gas. Similar results are obtained for India and Morocco.

Though counter-intuitive, the idea that adding more costly renewables can actually reduce portfolio generating cost is consistent with basic finance theory and derives from the statistical independence of renewables costs, which do not correlate (or *covary*) with fossil price movements. Adding renewables produces diversified portfolios with lower expected generating costs.

The principal implication of portfolio-based planning is that in dynamic and uncertain environments the relative value of generating alternatives must be determined not by evaluating alternative *resources*, but by evaluating alternative *resource portfolios*.

“Least-Cost” Versus Portfolio-Based Approaches in Generation Planning

For the last half century, *least-cost* planning has provided the basis for electricity generating capacity expansion in most countries. Planners were confident that by adding only so-called “least-cost” alternatives, they could expand the system at the lowest cost. Least-cost probably worked sufficiently well in a previous technological era, marked by relative cost certainty, low rates of technological progress, technologically homogeneous generating alternatives and stable energy prices. Today’s electricity planner, by contrast, faces a broadly diverse range of technological and institutional options for generating electricity and a future that is highly dynamic, complex, and uncertain. Attempting to identify the least-cost alternative in this environment is virtually impossible. Clearly, more powerful techniques are required if we are to develop robust generating strategies that remain economical under a variety of uncertain future outcomes.

Financial investors are used to dealing with uncertainty. They have learned that a portfolio of assets provides the best means of hedging future risk. Investors would not conceive of investing all their funds in a single stock on the basis of 30-year performance forecasts. Ridiculous as it seems, this is precisely what least-cost procedures do. Given the rapidly changing environment, it makes sense to shift electricity planning from its current emphasis of evaluating alternative *technologies,* to evaluating alternative generating *portfolios* and *strategies*. Mean-variance portfolio (MVP) theory is highly suited to the problem of planning and evaluating a nation’s electricity portfolios and strategies.[1] MVP has been applied to capital budgeting and project valuation [Seitz and Ellison, 1995], valuing offshore oil leases [Helfat, 1988], energy planning, [Awerbuch and Berger, 2003; Berger, 2003; Humphreys and McLain, 1998; Bar-Lev and Katz, 1976] and quantifying climate change mitigation risks [Springer and Laurikka]. In addition, the World Bank has established carbon funds using portfolio diversification ideas [See: Springer, 2003].

Energy planning processes need to abandon the preoccupation with finding “low-cost” alternatives and focus instead on developing efficient (optimal) generating portfolios. Efficient portfolios are defined by twin properties: they minimize expected cost (maximize return) for any given level of risk while minimizing expected risk for every level of expected cost (return). MVP principles require that planners evaluate the cost of conventional and renewables alternatives not on the basis of their *stand-alone* cost, but on the basis of their *portfolio cost*— i.e.: their contribution to overall portfolio generating cost relative to their contribution to the cost risks of a portfolio of generating resources.

Portfolio-Based Planning For Electricity Generation

The *Renewable Energy and Energy Efficiency Partnership* (REEEP) and the *Johannesburg Renewable Energy Coalition* (JREC) represent high-level international consortia interested in

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[1] Portfolio theory, an established part of modern finance theory, is based on the pioneering work of Nobel Laureate Harry Markowitz 50 years ago; see: Fabozzi, Gupta and Markowitz [2002] and Varian [1993].

focusing on the potential and affordability of renewable energy use. REEEP is explicitly committed to increasing the share of renewable energy in the global energy mix. Indicative as well as mandatory portfolio standards and renewables targets have already been implemented by the EU and a number of its member states as well as by other nations.[2] REEEP country partners and other nations have adopted such measures in order to progress on Kyoto compliance and climate mitigation. Fossil fuel independence and enhanced energy security have been additional motivating factors.

Much to their credit, policy makers from REEEP and JREC nations are pushing forward on the adoption of renewable energy targets in spite of the widespread belief that these technologies cost more and that increasing their share of the generating mix can only increase overall generating costs.

The idea that adding a more costly technology has to raise average generating cost seems obvious and compelling. Nonetheless, it is badly flawed. Estimating overall generating costs for a given mix involves assessments of long-term future cost *expectations* for highly uncertain fossil fuel and other outlays that have fluctuated significantly and unpredictably in the past. In other words, generating cost estimates reflect an assessment of how cost will behave in the distant future, 20 or 30 years from now. Long-term costs are highly uncertain. They cannot be directly observed or calculated the way cost is calculated for a bundle of fresh fruit at the market. Here the arithmetic is simple and intuitive: adding expensive strawberries to the mix, for example, raises the cost of making fruit salad.

The simple salad-making cost formula does not work for fuel and operating outlays or any other uncertain future cost stream.[3] Nonetheless, this is more or less how electricity planning models— the ones planners use to figure out what overall generating or "production" costs will be— estimate costs for given generating mixes. They figure that when you add €0.05/kWh wind energy to a €.03/kWh fossil generating mix, overall cost has to rise. In spite of what these models say, adding the appropriate share of renewable-based electricity, even if it costs more on a stand-alone basis, does not raise expected generating costs.

Figuring out how renewables (or other technologies) affect overall generating cost is more complicated. It is comparable to estimating how strawberries might affect the cost of salads that will be made over the next 20–30 years.[4] A number of variables will shape the answer to this problem. First, the cost of salad ingredients will vary over time— season-to-season and even day-to-day. The cost of future salad making is unpredictable as is the cost of generating electricity 20 years from now. Strawberries will sometimes be more expensive than other ingredients, thereby raising overall cost, but they might also be less expensive at times hence

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[2] The US Congress has also considered portfolio standards, but has not enacted such a measure.

[3] It does not work for financial portfolios either. For example, adding riskless government obligations yielding 3% to a stock portfolio producing 8% *raises* the expected return. For an explanation of this counter-intuitive result see Brealey and Myers or any finance textbook.

[4] Least-cost planners, by contrast, would try to identify the single salad mix that can be prepared each day over the next 20-30 years at the lowest cost.

bringing down the cost of salads. Renewables do the same: when gas prices are high, they are more competitive, as is now the case in the US and elsewhere.[5]

In order to estimate the future cost of any portfolio— whether fruit-salad or generating mixes— we need to figure out to what extent prices of the various ingredients move in unison. For example, if it turned out that strawberry prices statistically move *opposite* to other fruit prices, then including them in salads would have a beneficial effect. They would always mitigate the fluctuating and unpredictable future cost of salad-making. When other fruits increase in price, hence raising salad costs, strawberries prices would be falling thus moderating the cost increases. This is intuitive.[6] It is easy to understand the effect of adding strawberries or energy generating alternatives whose prices move opposite the rest of the mix. Such moves help moderate fluctuating portfolio prices.

The Effect of Fixed-Cost Technologies on the Generating Mix

It is easy to see that a generating technology whose costs are statistically negatively correlated to the rest of the portfolio can help mitigate portfolio cost swings. The cost of renewables-based electricity, however, probably does not move opposite to the cost of fossil-based generation. Rather, when taken over a sufficiently dispersed geographic region, the costs of wind, solar and other capital-intensive renewables are relatively fixed over time (which implies that their value is greater when fossil energy prices rise).[7] How will this affect *expected* future generating costs? This problem is less intuitive. It requires some statistics background and the inclusion of several additional factors. Unlike fruits in a salad, energy technologies last for a long time. Once we establish the generating mix, we are pretty much stuck with it for years if not decades. Over that period, society is exposed to risk— the risk that fuel and other generating costs will

How Does Financial Risk Affect Expected Generating Cost of the Electricity Mix?

Why fuss about the risk of generating portfolios? Because estimating the portfolio's generating costs without saying something about its risk is not very useful. It is similar to watching a movie with the sound turned off: you miss important parts of the story.

If a stockbroker advises Stock *X* because it has a higher return than *Y*, most investors would ask about the relative risks before buying either X *or* Y.

Likewise, if analysts are telling policy makers that one generating mix costs more than another, that estimate, *even if correct*, is not very helpful unless it also quantitatively informs policy makers about relative risk.

Unfortunately, policy-makers do not recognize that when they consider the cost-effects of greater renewables shares without considering the risk-effects, they are indeed watching the movie with the sound turned off and are hence missing critical aspects of the story.

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[5] For example, using conventional valuation, the *Union of Concerned Scientists* [2003] finds that a 20% renewable portfolio standard saves consumers money, even using EIA's more pessimistic renewable technology cost projections.

[6] Note this discussion focuses on cost, whereas portfolio theory as generally applied to financial assets deals with return. It can be shown however [Awerbuch and Berger, 2003] that cost is effectively the inverse of return, and that results are unaffected by whether portfolio optimization is accomplished on the basis of maximizing return or minimizing cost.

[7] Geographic dispersion diversifies and "evens out" the random risks of equipment failures and wind resource availability.

fluctuate. So, whether the ingredients are energy technologies or fruit for the salad, we cannot identify the best mixes without considering expected *cost* and expected *risk*.[8] Risk is defined in the traditional MVP sense as the *variability* or standard deviation of cost from one time period to the next: i.e. from day-to-day for salads or month-to-month and year-to-year for generators.

The cheapest salad— the mix with the lowest *expected* cost— is not necessarily the best choice. Why? Investors prefer certainty. Given two investments with an expected 10% return, rational investors will always choose the one that s less risky— the one whose year-to-year returns are less volatile. This is standard mean-variance theory. Investors are people, and people generally also prefer certainty in their financial obligations. For example, in the US they overwhelmingly choose long-term home loans with *fixed*-rate, guaranteed repayment streams. They do this, in spite of the availability of *variable*-rate home loans that are initially less costly, but whose future monthly payments are uncertain because they will rise and fall unpredictably with varying interest rates. Most people willingly pay more to get price certainty over time. Price stability has economic value— a fundamental finance idea. So, when it comes to mixes of salads or electricity generating alternatives, many people would not be pleased with a prescribed mix whose costs, though lower *on average*, fluctuate wildly from one time period to the next. Risk is as important as cost.

When we include the essential element of risk, the portfolio equation produces some powerful and counter-intuitive results that are part of the so-called *portfolio effect* discussed in any finance textbook. The portfolio-effect of adding a fixed-cost ingredient to the mix is powerful, if counter-intuitive.[9] Theory tells us that such an ingredient has the remarkable effect of *lowering* expected portfolio cost, adjusted for risk, even if its cost is *higher* than the remaining ingredients. Fixed-price strawberries will lower expected salad-making costs, adjusted for risk, even if they cost more than the remaining ingredients! Though counterintuitive, the mathematics is relatively simple and is based on the statistical idea that the fixed-cost ingredient— by virtue of the fact that its costs remain unchanged— is uncorrelated (more precisely, has a zero *covariance*) with the remaining ingredients. Statistical correlation affects the degree of diversification and hence the mix's overall risk.

Adjusted for risk, fixed-cost ingredients reduce *expected* portfolio cost, even if their stand-alone cost is higher.[10] But what about the caveat "adjusted for risk?" It means the following. The cost of the expensive strawberries is fixed,[11] while the other costs fluctuate over time. Suppose strawberries are expected to cost £4.00/Kg while the other ingredients will cost £3.00/kg *on average.* When £4.00 strawberries are added to a mix that costs £3.00 *on average,* the cost of the mix will indeed rise. But there is a second effect that most people forget— the fixed cost of the strawberries serves to reduce risk or overall cost fluctuations.

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[8] Expected value has a specific statistical meaning. It is the *weighted average* of all possible outcomes. The word is italicized to emphasize that it reflects this mathematical meaning.

[9] The *portfolio effect* in part implies that all efficient portfolios must contain some proportion of a fixed-cost ingredient; see: Brealey and Myers or any other text.

[10] This holds as long as the cost correlations for the remaining ingredients is less than 1.0, which is not a very limiting requirement. Portfolio effects becomes measurably pronounced when correlations fall below about 0.6

[11] Which implies that its expected value is known with near-certainty.

This is intuitive— with fixed strawberry prices, the cost of a mix consisting of 50% strawberries will fluctuate a lot less over time than one that has no strawberries.

This idea applies directly to generating portfolios. Passive, capital-intensive renewable technologies such as wind, geothermal, small hydro and possibly biomass and biogas have cost structures that are nearly fixed over time.[12] Like the strawberries in the salad, they might cost a little more on a *stand-alone* basis, but their costs are fixed or essentially *riskless*.[13] Viewed over a sufficiently dispersed geographic area, the operating cost of a generating portfolio with 50% wind will fluctuate a lot less than one with no wind.

Renewable Technologies Help the Generating Mix
They Affect Portfolio Cost *and* Risk

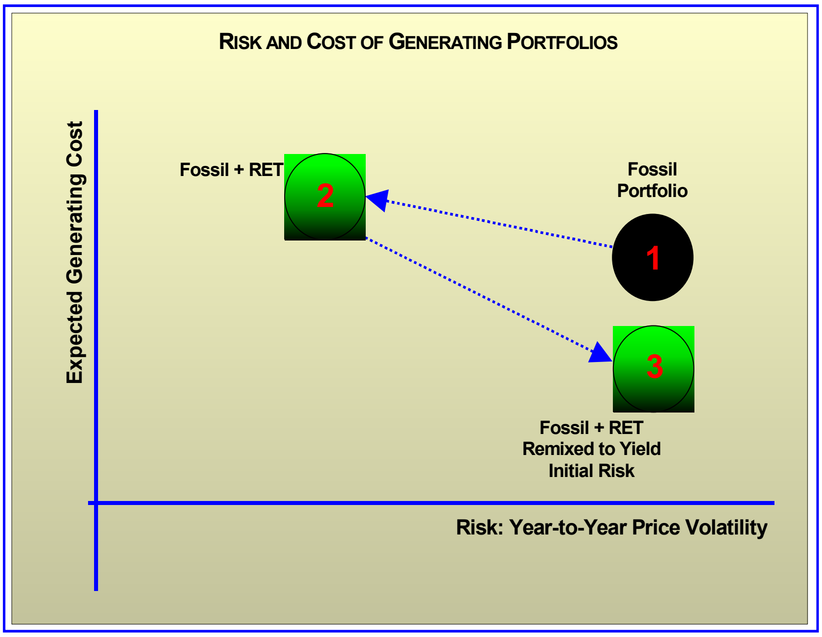

Figure 1: Absent a Risk Dimension Generating Cost Means Little

Figure 1 illustrates, beginning with a 100% fossil portfolio (a salad with no strawberries). When wind is added to the generating mix (or strawberries to the salad), portfolio costs rise and risk falls. This represents a move up and to the left. Now for the risk adjustment— and this is the important part. Suppose that after including strawberries (wind) in the prescribed

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[12] The finance theory aspects of this idea are further developed in Awerbuch, [November 2000]. PV is the quintessential passive, capital-intensive fixed-cost technology, although its grid-connected application in developing countries is not yet established. From a finance theory perspective, biomass and biogas might also be fixed-cost technologies to the extent that their price volatility is random and hence diversifiable. This implies that their fuel costs must be uncorrelated with economic events and with fossil prices and other generating costs.

[13] The term *riskless* is used in the finance theory sense to mean that their costs are at least *systematically* riskless, if not entirely fixed. Where their costs fluctuate, their movements either represent a very small proportion of total cost, or are uncorrelated with costs of major risk drivers such as fossil fuel costs. A technology whose costs move slightly, but not in unison with the costs of the predominant fossil technologies is almost as desirable as one with fixed costs.

mix, we could re-shuffle the mix so that we raised its risk back to the initial level before strawberries (wind) were added. If we could do this, we would find that adding the strawberries (or wind) served to lower the *expected* or average cost of the mix at that original level of risk.

Future fossil fuel costs and other generating outlays are random statistical variables. While their historic *averages* and variability (standard deviation) are known, they move unpredictably over time. No one knows for sure what the price of gas will be next month, just like nobody knows what the stock markets will do. Estimating the generating cost of a particular asset portfolio presents the same problems as estimating the expected return to a financial portfolio. It involves estimating cost from the perspective of its market risk. Talking about generating cost without also talking about financial risk is like watching a movie with the sound turned off— you miss a big part of the story.

Current approaches for evaluating and planning national energy mixes consistently bias in favor of risky fossil alternatives while understating the true value of PV, wind and similar fixed-cost, low-risk, passive, capital-intensive technologies. Recent evidence indicates that such technologies offer a unique cost-risk menu along with other valuable attributes that traditional valuation models cannot "see" [Awerbuch, 1993, 1995a, 1995b]. The evidence further suggests that fixed-cost renewables cost-effectively hedge the fossil price risk as compared to standard financial hedging mechanisms [Bolinger, Wiser and Golove, 2004].

Implications for Energy Security

A growing body of literature clearly suggests that fossil price levels and volatility depress macroeconomic activity as measured by GDP growth, employment and inflation. Energy mixes that are needlessly exposed to fossil risk reduce energy security. MVP helps policy makers evaluate the cost-risk of alternative generation mixes and create efficient portfolios that best meet energy diversity and security objectives. Efficient portfolios minimize society's energy price risk. This is a crucial aspect of energy security.

Energy security considerations generally focus on the threat of abrupt supply disruptions [EU Green Paper, 2001]. There is another more profound aspect of energy security: the risk of unexpected fossil fuel cost increases [Awerbuch and Berger, 2003]. Energy security is reduced when countries (and individual firms) hold inefficient portfolios that are needlessly exposed to fossil price risk. Portfolio diversity objectives may also include GHG emissions and other factors [Awerbuch, Stirling, Jansen and Beurskens, 2004].

Even relatively small percentage increases in fossil prices can yield sizeable economic losses through unemployment and losses in the value of financial and other assets. These costs can rise to the tens and even hundreds of billions of US dollars.[14] Efficient generating portfolios minimize national exposure to such price fluctuations, commensurate with minimizing overall generating costs and GHG emissions. Efficient generating portfolios expose society to the minimum level of risk needed to attain given energy cost and environmental objectives. This is a crucial aspect of energy security.

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[14] Sauter and Awerbuch, [2002] survey the literature and range of estimates. E. Papapetrou [2001] also provides an excellent literature survey.

Recent Portfolio Applications for the EU, US, and Mexico

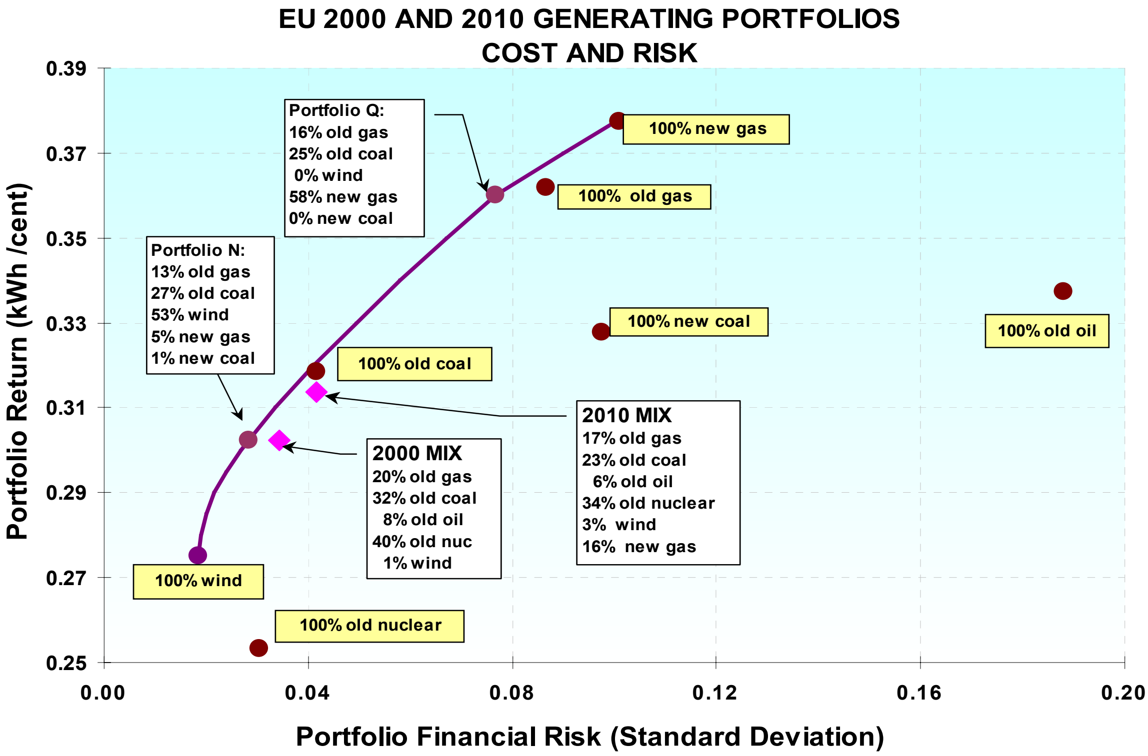
EU: Efficient Portfolios for Energy Diversity and Security[15]

This section summarizes the role of renewables on EU energy security objectives. It compares the risk-return properties of current and projected EU generating mixes to a set of optimal portfolios that minimize risk at any level of generating cost. The results indicate that there it is possible to construct lower cost/risk EU portfolios that also contain greater renewables shares. Such portfolio enhance both energy security and cost objectives.

Figure 1 shows the risk-return for various EU portfolio mixes. Portfolio risk is measured in the traditional manner as the standard deviation of historic annual outlays for fuel, operation and maintenance (O&M) and construction period outlays. Portfolio return is expressed as kWh/US-Cent— the inverse of generating costs. Higher returns in Figure 1 represent lower costs.

Figure 1: Cost and Risk of EU Generating Mixes

(Source: Awerbuch and Berger, 2003)



An infinite number of portfolio mixes exist on this graph at different risk-return locations. Each consists of a different mix of technologies. Figure 1 shows only those few portfolios that are significant. The heavy pink line on the graph is the efficient frontier (*EF*): the location of all optimal portfolios. Along the *EF*, return cannot be increased (i.e. cost cannot be reduced) without accepting more risk. Any portfolio that lies to the right and below the EF is inefficient in the sense that its cost can be reduced without increasing its risk and, conversely, its risk can be reduced without increasing its cost. There are no feasible mixes to the left of the EF.

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[15] This section based on Awerbuch and Berger [2003] and Berger [2003].

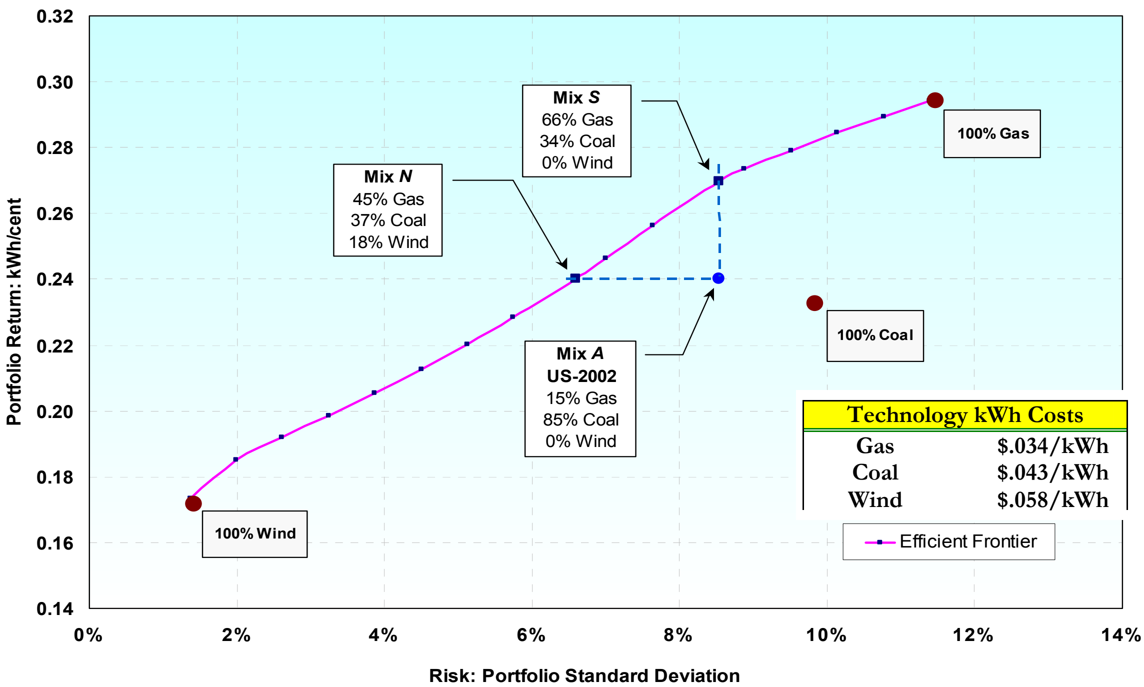
The EU-2000 mix has a generating cost of approximately 1/.30 or €0.033/kWh.[16] While wind costs about 10% more, increasing its share of the mix does not raise overall cost. Radically different portfolio mixes can produce similar risk-return characteristics. For example, compared to the year-2000 EU mix with its 1% wind share, Portfolio *N* contains 53% wind, yet it lowers risk and does not raise cost. While 53% wind shares may not be feasible given the limitations of existing power networks, the analysis generally supports the conclusion that adding moderate shares of wind— say 10-20%— to the EU mix does not necessarily increase generating cost. Similarly, though not shown on the graph, there exist portfolios to the left of the EU-2010 mix that include 20%-30% wind shares, but also do not increase cost.

US: The Effect of Renewables on the Generating Portfolio[17]

Figure 2 shows the risk-return for the 2002 US generating mix (Mix *A*), expressed in terms of coal and gas only (i.e. ignoring nuclear and oil-fired sources). Generating costs, the inverse of *portfolio return*, are given in the box. For example, a 100% wind portfolio has a return of approximately .17 which yields a kWh cost of 1/.17 = $.058. A powerful point emerging from Figure 2 is that the US policy of continued gas expansion raises risk rapidly while yielding only small cost reductions (Awerbuch, 1999). A move from Mix *A* to a mix of 100% gas, for example, increases risk by 35% (from 8.5% to about 11.5%) but reduces cost by less than 9%. (.27/.295).

Figure 2

Risk and Return for 3-Technology US Generating Mix



Source: Awerbuch, Stirling, Jansen and Beurskens, 2004

Mix *A* lies below the *EF*. This implies that policy makers can improve cost and risk by adjusting the mix over time. For example Mix-*N* offers the same expected cost as Mix-*A* but with lower risk. It is therefore more desirable. Mix-*N* contains 18% wind thus contradicting

[16] New gas costs approximately €0.026/kWh (1/0.38).

[17] This section based on Awerbuch, Stirling, Jansen and Beurskens, [2004].

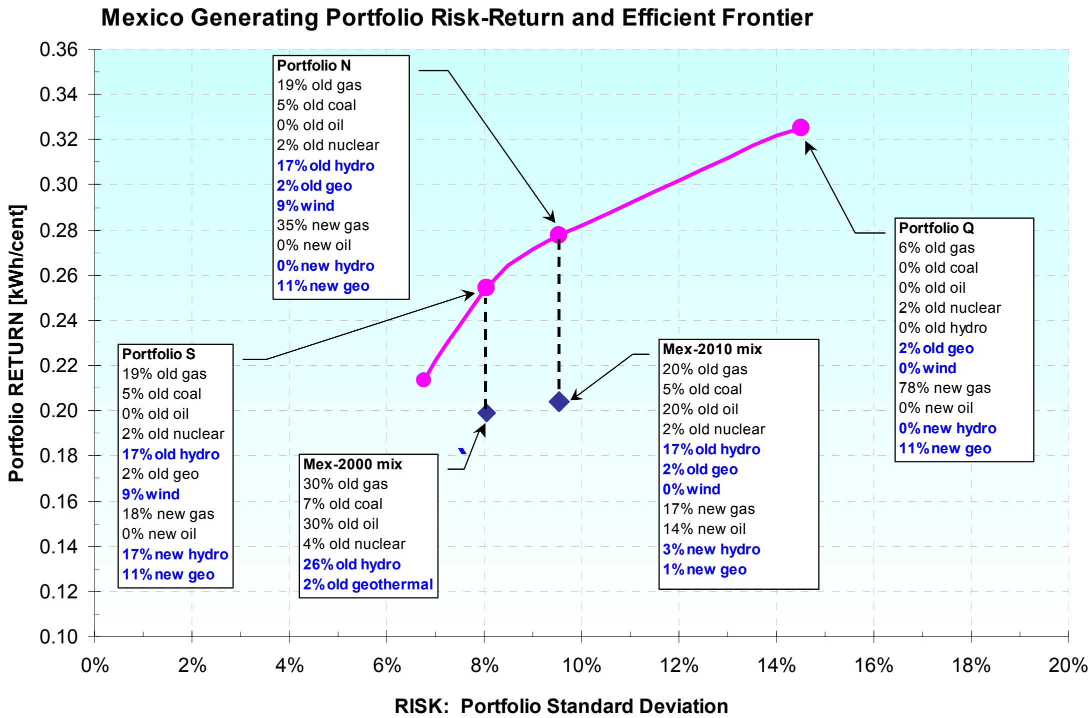
the widely held notions that adding wind to the US mix will increase costs. Mix *N* again demonstrates the key portfolio idea: although wind costs 70% more than gas, it can displace other technologies in the existing US mix in such a manner as to reduce risk without increasing overall generating cost. This "free-lunch," widely ignored in public and corporate policymaking, is created by the portfolio effect.

The move to Mix A from Mix *N* reduces risk by 23% (from 8.5% to 6.6%) without changing cost. Mix-*S,* by comparison, lowers generating cost by 12% relative to Mix *A*, but leaves risk unchanged. *S* is the lowest-cost mix possible at this level of risk. As we move along the *EF* from *S* to *N,* the share of wind rises from 0% to 18% of the mix, replacing primarily gas. Moves along the *EF* may satisfy different individual cost-risk preferences but they create no net gains. It cannot be said that Portfolio *S* is superior to *N.* However, either is better than the US-2002 mix.

Mexico: Evaluating Planned Generating Mixes[18]

Figure 3 shows the risk-return for various Mexico generating portfolios. The planned MEX-2010 portfolio has a cost of about 4.8 cents/kWh. *Portfolio N* offers a considerable improvement. Without increasing risk, it raises return, or lowers cost to 3.6 US-cents/kWh (1/.28), a reduction of by 25% or 1.2 US-cents/kWh. No wind is planned for the MEX-2010 mix. *Portfolio N*, by contrast, includes 9% wind (and 11% geothermal), which largely displaces "old" or existing oil. Wind costs 5 US-cents/kWh, twice as much as gas.

Figure 3



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18 This section based on the REEEP-UNEP project results; (see: Awerbuch, Jansen and de Vries, [2004]). While Mexican results are discussed, similar outcomes were obtained for Morocco, and India.

Conclusions

Today's dynamic and uncertain environment requires robust electricity planning procedures that have evolved from an outmoded least-cost paradigm to appropriate portfolio-based approaches that accommodate market risk. Portfolio analysis reflects the cost inter-relationship (covariance) among generating alternatives. Though crucial for correctly estimating the overall portfolio cost, electricity planning models universally ignore this fundamental statistical relationship and instead resort to sensitivity analysis as a means of dealing with risk. Sensitivity analysis cannot replicate the important cost inter-relationships that dramatically affect estimated portfolio costs and risks. It is not a substitute for portfolio-based approaches.

Mean-variance portfolio theory represents a well-tested approach for evaluating national electricity strategies.[19] The MVP framework offers energy diversity concepts and solutions that are considerably more robust than arbitrarily mixing technology alternatives. For example, MVP makes it clear that the typical gas-coal generating portfolio offers little diversification. While it may insulate from random risk— e.g. transportation shortages and particular fuel flow stoppages, it provides little insulation from the systematic risk of coal and gas price movements, which have historically been highly correlated.[20]

Energy analysts and policy makers today face a future that is technologically, institutionally and politically complex and uncertain. In this environment, MVP techniques can help establish renewables targets and portfolio standards that make economic and policy sense [e.g. see Jansen, 2003]. They can also provide the analytic basis policy-makers need to devise efficient generating portfolios that maximize energy security while minimizing expected cost. These are vitally important energy issues.

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[19] Other techniques have also been applied, e.g. A.C. Stirling [1996, 1994], develops maximum-diversity portfolios based on a considerably broader uncertainty spectrum. Though radically different in its approach, his diversity model yields qualitatively similar results.

[20] Increasing use of contracts may mitigate this historical relationship by pricing each fuel more on the basis of its costs. However, given severe shortages for a particular fuel, suppliers may provide additional quantities of other fuels only at higher prices.

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