IMPROVING ENERGY SECURITY IN PACIFIC ASIA: DIVERSIFICATION AND RISK REDUCTION FOR FOSSIL AND NUCLEAR FUELS

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ABSTRACT

The purpose of this paper is to provide a methodology applicable to Pacific Asia for evaluating energy supply dependence across fuels and for particular fuels—with a primary emphasis on nuclear fuels. The methodology can be used to compare fuel types and to evaluate economic costs for improvements in supply security. An analytic approach is developed to quantify supply dependence, with suggested mechanisms for subjectively weighting factors that may be of particular importance in Pacific Asia. The basic principle is similar to that used for dealing with many types of risk diversification. The level of diversification alone is not a complete measure of supply security since one must also account for the specific risks associated with particular supply sources as well as systematic risk associated with the market for a particular fuel. These risk factors are also addressed in the paper.

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1. INTRODUCTION

Energy security is just one aspect of national and regional security. While energy crises of the past several decades have received a great deal of attention, resilient domestic economic and financial structures and regional linkages, environmental risk reduction, and resolution of territorial disputes in a post-Cold War environment, have recently emerged as important aspects of national and regional security. These are not independent issues. There are strong linkages between energy and the environment, rapid changes in energy prices can destabilize fragile financial structures, and resolution of territorial disputes can be linked to concessions in energy or other trade.

While Japan and the other nations of Pacific Asia have been immensely successful in terms of economic growth and exports they are largely dependent on foreign sources of energy. This dependence has sometimes led these nations to pay more for energy, to pursue alternative technologies, and even to frame foreign policies to enhance energy security. However, while there have been intense fears in some of these nations—especially Japan—regarding energy supply security, it is neither clear that such actions have secured significantly increased security nor will do so in the future.

A fundamental problem is that there are few analytic methods to evaluate the degree energy security. Lacking such methods, it is difficult to make clear cost-benefit tradeoffs between financial, technical and policy measures intended to improve energy security or to evaluate energy security measures in a larger policy context.

The energy security debate is often framed in physical terms rather than in economic terms. World markets in most energy commodities are primarily driven by economic forces. According to the economic view, a nation can adapt to changed energy market conditions simply by out-bidding other buyers. In the 1979 oil crisis, for example, Japan suffered less physical disruption than the United States, simply because oil was drawn to the region by higher prices, while the US was still under a system of price controls. Of course, higher prices had negative effects on the Japanese economy, as it did on most other economies.

The true measure of dependency thus depends on a combination of physical and economic conditions. One must thus focus on a combination of factors and policy responses. For example, a shift in industrial policy away from energy-intensive industries and toward knowledge-based industries may have as much, or greater, consequence as changes in energy-supply policy.

These observations, however, do not fully capture what may be a uniquely Japanese (and perhaps broader Pacific Asian) emphasis on physical supply security; a resource-poor nation has a predisposition to view matters in physical terms. The purpose of this paper is to provide a methodological basis for evaluating energy supply dependence across fuels and for particular fuels—with a primary emphasis on nuclear fuels—but on a basis that may be used for comparison between fuel types and for evaluating economic costs for improvements in supply security.

In the following, we first develop an analytic approach to quantifying supply dependence, with suggested mechanisms for subjectively weighting factors that may be of particular importance in Pacific Asia. The basic principle is that used for dealing with many types of risk diversification. The level of diversification alone is not a complete measure of supply security, since one must also account for the specific risks associated with particular supply sources, as well as systematic risk associated with the market for a particular fuel. Later in this paper, we will see how to deal with these risk factors.

2. QUANTIFYING SUPPLY DIVERSIFICATION

The approach initially developed here is based on the classic Herfindahl measure of market concentration. While this approach has found its widest application in antitrust law, it is adaptable to measuring dependency. The Herfindahl index is simply the sum of the squares of market fractions controlled by individual firms or, in our case, supplier countries, and even fuel types.

The simple Herfindahl—or diversification—index may be written as:

$$H = \sum_i x_i^2$$

where x_i is the fraction of total supply from source "i."

That is, in estimating diversification of supply by this approach, if there is only one supplier the index is 1, if there are ten suppliers of the same size the index is 0.1. If there is one dominant supplier with 90% of the market, and only one other supplier with 10%, then the index is 0.82. A lower index means greater diversification of supply. The reciprocal (1/H) of the Herfindahl index can be viewed as the number of equivalent suppliers.

We can first apply this approach to examine diversification among fuels. As long as there is little correlation between risks associated with various fuel markets—which is most often the case—our simple diversification index is a good measure.

Second, for any given energy market, we can compute the average diversification of supply, either by supplier company, country, or country-group, based, for example, on fuel production levels or exports. This might then be compared with Pacific-Asian actual procurement commitments to determine what might be necessary to increase diversification of supply. As noted, diversification is one of several mechanisms to increase energy security, just as it is to minimize risk in financial or other markets. There are a number of ways in which Pacific Asian nations can increase diversification and thus reduce their respective energy vulnerabilities.

In a later section, we will extend this formalism to include risk associated with particular fuels or, for a given fuel, risk associated with particular suppliers.

3. FUEL DIVERSIFICATION

Diversification among fuels is obviously a major strategy for reducing the risks of overall dependency. Despite efforts to diversify, Japan and most other Pacific Asian nations are still overly dependent on imported oil. The following analysis provides a convenient analytical way of measuring the relative level of diversification among fuel types.

World energy supply is dominated by five types of energy generation: oil, gas, coal, nuclear, and hydro. If a nation were to use all five of these sources equally (assuming they are ultimately interchangeable in use), then the diversification index would simply be:

$$H_{fuel} = 5(\frac{1}{5})^2 = 0.20$$

On average, the world does not use all five sources in equal proportion. According to data compiled in the BP Annual Statistical Review of World Energy, world energy consumption in 1996 was 8380 million tonnes oil-equivalent, with the following breakdown by fuel:

Table 1
1996 WORLD ENERGY DISTRIBUTION
(000 b/d)

FUEL	MILLION TONNES OIL-EQUIVALENT	FRACTION OF TOTAL
Oil	3312.8	0.395
Gas	1971.6	0.235
Coal	2257.0	0.269
Nuclear	621.3	0.074
Hydroelectric	218.1	0.026

We can now compute the average world diversification index among fuel types. By adding the squares of the fractions in the table, we find that the average diversification index is 0.290. This value is obviously dominated by hydrocarbon fuels. Indeed, if there were no nuclear power or hydroelectric, the index would be 0.294, virtually the same. The existence of nuclear and hydroelectric so far make only modest contributions to increasing world diversification among fuel types (i.e., nuclear and hydroelectric combined reduce the fuel diversity index by only 1.4 percent).

Japan's fuel diversification index—at 0.358—is significantly larger (less diversified) than the world average of 0.290. By contrast, the diversity index for the United States is 0.291, extremely close to the world average. Great Britain is similar, at 0.293. Canada's mix is even better, at 0.256. The diversification index for the Asian-Pacific region as a whole is 0.367; without China (which uses large amounts of domestic coal), the latter index is 0.348. Japan is thus not much different than the region as a whole.

It is useful to look at the fuel components that contribute to the diversification index for consumption by several countries and groups of countries. Table 2 shows the contributions to the diversification index for several countries and groups of countries. Note that the figures shown are not fractions of supply but rather the squares of these fractions, in order to show the contributions to the diversification index in the right-most column.

Table 2
1996 ENERGY CONCENTRATION BY FUEL
Selected Countries and Areas
(000 b/d)

	X_i^2					$\sum_i X_i^2$
COUNTRY	Oil	Gas	Coal	Nuclear	Hydro	TOTAL
World	.156	.055	.073	.005	.001	.290
OECD	.183	.053	.042	.013	.001	.292
Asia Pacific (w/o China)	.254	.019	.069	.006	.000	.348
European Union	.197	.047	.026	.025	.001	.296
Japan	.289	.014	.031	.024	.000	.358
United States	.153	.071	.059	.007	.000	.291
Sweden	.154	.000	.003	.190	.010	.357
France	.140	.014	.003	.178	.001	.336

This table makes clear that there are a number of national or regional fuel use choices that can yield the same diversification index. The US more or less replicates the world consumption pattern. The OECD, as a group, uses somewhat more oil and somewhat less coal, but also somewhat more nuclear to achieve a similar index. The Asia Pacific region (without China) uses significantly more oil—at the expense of coal consumption—and about the same amount of nuclear; the net result is a diversification index significantly worse than the world average. The examples of Sweden and France are quite interesting: both countries use about the same fraction of oil as the world as a whole but much less gas and coal. In compensation, nuclear makes a large contribution to supply. However, the high dependency on nuclear results in these two nations having about the same poor diversification index as Japan and Asia-Pacific. That is, one can be as overly dependent on nuclear as on oil.

Japan and the Asia Pacific region could improve their energy supply mixes to achieve greater diversification, even by using a mix of energy sources different from that of the world averages. On a regional basis, more natural gas (likely in the form of LNG) and coal could be used to reduce the dependence on Middle East oil.

For Japan, an increase in the use of nuclear power could improve its fuel diversification index. Japan has recently proposed adding 20 GWe of new nuclear capacity by 2010 to reduce carbon emissions. If this were accomplished, it would result in a modest improvement in its fuel diversification. A 1000 MWe nuclear plant operation at a 75% capacity factor can displace about 1.6 million tonnes of oil used for electricity generation each year. If we assume no changes in the above 1996 energy consumption figures (i.e., no growth through 2010) but shift 33 million barrels of oil-equivalent consumption (i.e., 20 GWe of new nuclear) from the oil column to the nuclear column, the resultant diversification index is reduced from 0.358 to 0.316.

To reduce the fuel diversification index to 0.29—the world average—Japan would have to shift about 70 million tonnes oil-equivalent to nuclear, a capacity addition of nearly 40 GWe, without otherwise increasing oil consumption. Of course, if energy consumption in Japan increases between now and 2010, the increase in nuclear would have to be even greater to achieve similar diversification. With only one nuclear power plant now under construction, and some growth in consumption of fossil fuels, it seems unlikely that Japan can substitute nuclear power for oil at the above levels. In this case, additional improvements in diversification would have to come from increased use of LNG and coal.

From a regional perspective, improved diversification could be achieved by increasing use of indigenous fossil fuels, shifting energy-intensive industries even more toward countries with such resources, particularly as growth occurs. To the extent that consumer use of electricity is growing in Japan and other countries, it is difficult to reduce dependence, after all conservation measures are taken, without imports of fossil fuels and expansion of nuclear power.

4. INDUSTRIAL GLOBALIZATION AND REGIONALIZATION

With the globalization of a particular country's economic activity, the energy dependence of that country must be regarded as a combination of the energy dependencies of countries in which industrial output is performed. Thus, by building factories in other nations, Japan could in principle reduce the vulnerability of its own economy to energy supply uncertainties. For example, Japan would gain little by building factories in Taiwan or South Korea—which have energy dependencies similar to Japan itself—but more to gain by exporting energy intensive industrial activity to Malaysia and Indonesia which are self-sufficient in oil and natural gas, or to the US or Canada, whose energy supply profiles are close to or better than international averages.

The reduction in vulnerability of such globalization can be achieved by selectively exporting energy intensive industrial activity to energy self-sufficient nations and emphasizing non-energy intensive industries at home. Alternatively, Japan or another country dependent on imported energy can reduce its vulnerability by importing energy-intensive raw materials, such as steel and cement. These industrial measures can be more effective and cheaper than trying to compensate by expanding expensive new energy supply sources at home. In this connection, it should be noted that the time frame for significantly changing the energy supply mix is comparable to that for changing industrial mix: that is, one does have a choice.

Redistributing energy intensive industries can also shift the burden of at least some environmental and other problems, which are also aspects of national security. Energy use has local, regional and global environmental consequences. The burning of fossil fuels usually results in local and regional pollution and results in increases in greenhouse gases, a matter of global consequence. Nuclear and hydroelectric power do not have these direct effects (there are indirect effects since the building of nuclear facilities and dams requires significant use of fossil fuels, especially if the growth rate of such non-fossil fuel sources is comparable to the energy pay-back time for such sources). However, the creation of fossil waste is paralleled in the case of nuclear power by the creation of nuclear waste. In both cases there are societal tradeoffs, locally, regionally and internationally.

Shifting energy-intensive industries to developing countries with indigenous resources may hold an additional incentive. If industrialized countries like Japan agree to reduce carbon emissions from fossil fuels, but developing countries are not subject to such restrictions, desires to reduce fossil fuel dependency in industrialized countries (and to build more nuclear plants) will be further justified on "environmental" grounds. For example, Japan's plan to build an additional 20 GWe of nuclear capacity could shift about 750,000 barrels a day of oil consumption to less-developed countries in the region. The overall result of a multilateral agreement on carbon emissions may therefore simply result in a redistribution of industries, energy use, and environmental impacts.

The diversification indices developed above do not yet include a distinction between indigenous and imported fuel supplies. In a later section, we shall indicate how to reflect the relative certainty or uncertainty of energy supply sources. However, it should not be assumed that domestic energy supplies are much less risky than imported supplies. Use of domestic sources can be disrupted by accidents, strikes, newly discovered environmental effects, and other factors.

5. SUPPLIER DIVERSIFICATION

We have thus far considered only diversification among fuels. For each such fuel, there is potential for reducing overall risk by diversification among suppliers. For example, depending on only one or two suppliers for oil or nuclear fuels can be quite risky. In principle, we can calculate the maximum potential diversification for each fuel based on the pattern of supply availability. This maximum theoretical diversification can be compared with a given country's actual pattern of procurement.

OIL In the case of oil, there is a large number of suppliers and thus a high potential for diversification. However, in principle at least, OPEC action can suddenly reduce the effective number of suppliers and thus the potential for diversification. Using the same formalism as above, we can calculate a theoretical maximum diversification index for oil, and then see how it changes if and when the oil cartel acts as a single supplier.

If we use oil production data, which are more readily available than export data, the potential diversification index is a very low 0.06; that is, there is potentially a very high degree of diversification. However, if we treat OPEC as a single supplier, the index for potential diversification increases to 0.20. That is, the oil market can suddenly undergo a major structural change. In an earlier book (*Energy and Security*, Harvard/Harper & Row, 1980), I termed this a "phase transition" like that from fluid water to ice: the behavior of the market is quite different in one "phase" than in another.

Export and import data for geographical regions are available from BP and thus we can construct a maximum potential regional supply diversification index, against which procurements by a country or consuming region can be compared. Table 3 shows the flows of oil between regions and the contributions to regional diversification indices.
Based on exports of oil (rather than production) the world average supply diversification index is 0.242. However, different consuming countries have chosen a supply mix that deviates from this

theoretical minimum. The United States and Western Europe, for example, buy a higher percentage of oil from North and West Africa, as well as from Venezuela and Colombia, than does Japan. Diversification indices for the US and Western Europe are consequently lower, at 0.209 and 0.236 respectively, both better than the world average. In contrast Japan and the Asian Pacific region are much more dependent on the Middle East than other consuming regions with resulting diversification indices of 0.604 and 0.628, respectively.

Obviously, Japan, and the Asia-Pacific region generally, could do a great deal to diversify oil supply. The reasons for this increased dependence presumably are the result of marginal economic factors: transportation cost differences and the ability to burn cheaper heavy sour crude for electricity generation. The cost of much greater diversification of supply sources is probably less than ten percent of the total oil bill. The cost of diversification can be compared with the cost of other (including non-oil) measures to reduce risk.

As will be discussed later, diversification among suppliers can greatly reduce risks due to dependence on *particular* suppliers, but not the overall market risk. That is, a consuming country will still be exposed to risk factors associated with overall market supply and prices. Other mechanisms must be used to reduce the general, or systematic, market risk.

NUCLEAR FUEL The supply of nuclear fuel to the reactors of a particular country requires a series of processing steps: uranium must be mined and purchased; it must then be converted to UF6; then enriched; then fabricated into fuel elements specific to the reactor in which it will be used. Each of these steps involves dependence on a particular set of suppliers of raw material or services.

The potential for diversification in uranium supply is quite high. Table 4 shows production by country. While Canada, Australia, and Niger are the largest producers and exporters, there are quite a number of potential other suppliers. Based on production numbers, the *potential* diversification index is a low 0.16, compared with a oil index of 0.25. Based on exports, the uranium index is much lower than that for oil.

Consumption of uranium in Japan is approximately 8,000 metric tonnes uranium (MTU) per year and that of Pacific Asia collectively is about 11,000 MTU. World production in 1996 was about 36,000 MTU. While detailed data on uranium procurements for Japan and Pacific Asia are not available, patterns of procurement appear to mirror world production patterns (an exception may be Japan's larger than average dependence on production from Niger). The high level of diversification in uranium should be contrasted with the low level of diversification for the Asia-Pacific region in the case of oil (the diversification index for which, on a regional basis, was 0.63 due to heavy dependence on Middle East supply). Moreover, the great majority of uranium supply to the Asia-Pacific region and Japan is from quite secure sources (e.g., Canada and Australia).

Table 4
URANIUM PRODUCTION DIVERSIFICATION

Country or Area	1996 Production (tU)	Including MOX		Without MOX	
		S_I	S_i^2	S_i	S_i^2
Argentina	29	0.000	0.000	0.000	0.000
Australia	4,974	0.137	0.019	0.141	0.020
Belgium	28	0.000	0.000	0.000	0.000
Canada	11,788	0.326	0.106	0.335	0.112
China	500	0.014	0.000	0.014	0.000
Czech Republic	600	0.017	0.000	0.017	0.000
France	930	0.026	0.000	0.026	0.000
Gabon	565	0.016	0.000	0.016	0.000
Germany	40	0.001	0.000	0.001	0.000
Hungary	200	0.006	0.000	0.006	0.000
India	200	0.006	0.000	0.006	0.000
Kazakstan	1,320	0.036	0.001	0.038	0.001
Namibia	2,452	0.068	0.005	0.070	0.005
Niger	3,320	0.092	0.008	0.094	0.009
Pakistan	23	0.000	0.000	0.000	0.000
Portugal	15	0.000	0.000	0.000	0.000
Romania	100	0.003	0.000	0.003	0.000
Russia	2,000	0.055	0.003	0.057	0.003
South Africa	1,440	0.040	0.002	0.041	0.002
Spain	255	0.007	0.000	0.007	0.000
Ukraine	500	0.014	0.000	0.014	0.000
USA	2,420	0.067	0.004	0.069	0.005
Uzbekistan	1,500	0.041	0.002	0.043	0.002
MOX	*1,000*	*0.028*	*0.000*	-	-
Total	36,199	1.000	0.153	1.000	0.161

Much has been made of the contribution to energy security of reprocessing of spent fuel and recycling of uranium and plutonium. Using our diversification approach, we can quantify the effect of use of plutonium fuels. According to Uranium Institute estimates (UI Market Report, 1996), plutonium mixed oxide fuels *could* currently add the equivalent of about 1000 MTU to world supply, less than a three percent increase. By 2010, use of MOX could add (according to utility plans) the equivalent of about 3,000 MTU of supply. Of course, use of MOX has not reached these levels yet and plans for 2010 may not be achieved. By comparison, there are many ways to increase production of, and secure access to, natural uranium by an amount equal to the use of MOX, particularly on a ten-year time horizon.

As shown in Table 4, the effect of 1,000 MTU-equivalent use of plutonium on our world diversification index today would be to reduce (improve) the diversification index for uranium by 0.007, from 0.160 to 0.153, not a very large change.

For Japan, current policy is to use MOX in about ten reactors (one-third core) by the year 2010. Assuming Japanese nuclear capacity of 56 gigawatts electric in 2010, MOX use would account for about six percent of fuel requirements by that date. Under perhaps the most optimistic scenario, plutonium might displace about 1,000 MTU-equivalent, out of the 10,000 MTU required annually by 2010, or about 10 percent. It is quite unlikely that other nations in the Asia Pacific region would make significant use of plutonium fuels and thus, on a regional basis, the plutonium displacement effect on uranium would only be about five percent overall.

As noted above, nuclear fuel supply involves more than just uranium. Indeed, the potential, and actual degree of, diversification of nuclear fuel supply is not restricted by uranium supply as much as it is by a high level of concentration of supply of conversion and enrichment services and, in the case of plutonium, limited opportunities for diversification of reprocessing and MOX fabrication services. There are only four sources of conversion services in the West, in the US, Canada, France and the UK. For enrichment services, the US still provides more than 80 percent of Japanese enrichment services, with the remainder from Eurodif (France) and Urenco (a tripartite consortium of the UK, Germany and the Netherlands). The same is true for most of the Asia-Pacific region (though some countries and companies will buy from Russia). In the case of reprocessing and MOX fabrication, Japan is (despite a small domestic effort) largely dependent on France and the UK. These supplies are not without uncertainty, as recent government actions in France demonstrate.

For Japan, the diversification index for enrichment is about 0.66, and that for MOX supply is about 0.5. Both of these are much higher than the diversification index for uranium supply. Thus, diversification of nuclear fuel supply for Japan, and East Asia more generally, is limited largely by the lack of diversification of enrichment supply, not by that for uranium. In the case of plutonium fuels, even with part of supply coming from domestic sources, the opportunities for diversification are extremely limited.

6. TAKING ACCOUNT OF RISK

Thus far, we have been concerned largely with measuring the degree of diversification. Of course, the main reason to diversify supply, either among fuels or among suppliers of a particular fuel, is to reduce the overall risk and consequence of disruption of supply in particular fuels or from particular suppliers. In this section we shall discuss refinement of our analytical approach to include the degree of risk associated with individual suppliers and the effect on risk reduction through diversification.

Our starting point in evaluating risk is modern portfolio theory, which was developed to deal with the problem of risk in investing in the stock market. Clearly it is better to invest in a diverse set of companies than to invest in only one company. This is the same basic intuition that led us to consider diversification among energy types and among suppliers. However, it is generally not wise to make investment, or diversification, decisions without considering the risks associated with particular stocks, or energy supply sources.

In both cases, there are two kinds of risk: that associated with a particular company (or supplier) and that associated with general, or *systematic*, market risk. The latter is the risk that economic, political or other factors may cause most or all company stock prices (or energy supply quantities and prices) to increase or decrease. Within a given market, it is possible to diversify away the risk specific to individual suppliers, but it is much more difficult to eliminate the systematic, or market, risk. In a later section of this paper we will examine some mechanisms for reducing the systematic or market risk for energy.

Given that financial markets are international in nature, there is—to first approximation—only one stock market. That is, changes in one stock market are quickly transmitted to other stock exchanges. This is not the case with energy supply: one can diversify among fuel markets and, within each fuel market, among suppliers. That is, there are two diversification mechanisms available to reduce risk. There is much to do in the Asia-Pacific region on both types of risk reduction: the region is unusually dependent on oil, and, in the oil market, on the Middle East.

Unlike the equities market, there is little chance that physical reductions or price increases in nuclear fuel supply would be correlated with reductions in oil, gas, or coal supply. There is also little physical supply correlation between fossil fuels, but in the case of oil and gas at least there can be a price relationship.

CHARACTERIZING RISK Let us begin with the stock market to clarify the basic approach. If one buys stock in a single company, its price can be expected to vary over time. The degree of this variation, or variance is different for each stock. In general, the variance for a single stock is greater than that of the market as a whole: some stocks go up while others go down and the changes average out. The *variance* in the price of an individual stock "a" over time is usually denoted by the square of the standard deviation and designated by s_a^2.

To be explicit, let us assume we have a monthly time series of prices for stock "a" (later, we will use a series of monthly production or export quantities for oil or other fuels). In this case, the variance in price "p" for stock "a" is calculated according to the following formula:

$$s_a^2 = \frac{\sum_{i=1}^{N} (p_{monthi} - p_{average})^2}{N},$$

where $p_{average}$ is the average price over the N-month period.

The correlation between price movements "p" and "q" in stocks "a" and "b" is designated by the *covariance*, which is calculated by summing the products of deviations from the average as follows:

$$s_{ab} = \frac{\sum_{i=1}^{N} (p_{monthi} - p_{average})(q_{monthi} - q_{average})}{N}.$$

It is convenient to define a *correlation coefficient* r_{ab} which relates the covariance of the two stocks to the individual variances (more precisely, we are using the standard deviations—the square roots of the variances):

$$r_{ab} \equiv \frac{s_{ab}}{s_a s_b}.$$

This correlation coefficient r_{ab}, which is a number between +1 (complete correlation) and -1 (anti-correlation), is extremely useful. Later, we will use it to measure the degree to which one energy supplier either compensates for, or aggravates, loss of supply from another supplier.

In our application of this approach to energy markets, s_i^2 is the variance in production or exports (whichever we choose) of a particular producing country "i." If a change in production in country "i" was correlated with a change in production in country "j," this relationship would be quantified by the covariance s_{ij}. For example, if OPEC imposed quotas on its members, a reduction in exports in one OPEC member country would be highly correlated with a reduction in another member country. In this case, r_{ij} could be +1. One obviously does not want to construct a portfolio of stocks or energy supply in which supply changes are totally correlated, since then we are exposed to the worst case: disruption in one supply is guaranteed to be matched by disruption in the other.

However, if a reduction in production or exports from country "i" were compensated for by an increase in production or exports from country "j," the correlation coefficient could be -1. Obviously, one wants to make supply arrangements where covariance is as small as possible: zero, or -1 if feasible.

To see the relationship between covariance and diversification, let us consider a situation in which we have two supply sources. Let us assume that fraction x_1 of total supply comes from supplier "1" and fraction x_2 (the remainder) comes from source "2." (so that $x_1 + x_2 = 1$). The correlation coefficient between supply source 1 and source 2 is r_{12}. We then have the following matrix of variances for our simple portfolio of supply:

	SUPPLIER 1	SUPPLIER 2
SUPPLIER 1	$x_1^2 s_1^2$	$x_1 x_2 r_{12} s_1 s_2$
SUPPLIER 2	$x_1 x_2 r_{12} s_1 s_2$	$x_2^2 s_2^2$

The overall supply portfolio variance (one's exposure to risk) is then

$$\text{Portfolio Variance} = (x_1^2 s_1^2) + (x_2^2 s_2^2) + 2(x_1 x_2 r_{12} s_1 s_2)$$

That is, the portfolio variance is equal to the sum of the variances increased or reduced by the amount of correlation or anti-correlation between the behaviors of suppliers 1 and 2. If there is perfect correlation between the behaviors of both suppliers, then the standard deviation would just be the weighted average of the standard deviations of the two supply sources (i.e., $(x_1 s_1 + x_2 s_2)^2$). In this case, one would want to shift supply (the fraction x) toward the source with the lowest standard deviation (s), giving the least chance of change in supply.

If the behavior of supplier one is exactly offset by the behavior of supplier two, so that r_{12} = -1, it is possible to allocate supply between sources such that the total supply portfolio risk is zero! This occurs when we take fractions of supply from sources in inverse proportion to their riskiness. This is when:

$$(x_1 s_1 - x_2 s_2) = 0, \text{ or } \frac{x_1}{x_2} = \frac{s_2}{s_1}$$

As we will show below, we can estimate the standard deviation and the correlation coefficients for individual suppliers and pairs or groups of suppliers based on historical data. We will use oil production during the 1990-91 Gulf War as the example. In addition to using historical data, policy and market experts can evaluate and quantify future risks and thus guide future procurement strategies.

7. RELATIONSHIP TO THE DIVERSIFICATION INDEX

In the earlier half of this paper, we developed a diversification index based on the Herfindahl approach. In that approach, we constructed an index using fractions of total supply. What we learn from the modern finance portfolio approach is that we can extend this formalism to include uncertainty or risk associated with the amounts of supply from particular sources.

The diversification index was defined as the sum of squares of fractions of supply coming from individual sources. In effect, the Herfindahl approach assumes that all sources are equally certain or uncertain. With the help of finance theory we can now take into account variations in the past (as determined by historical behavior) or estimated future security of supply. Instead of a supply portfolio diversification index of

$$H = \sum_i x_i^2$$

we can use a supply portfolio index equal to

$$\text{P} = \sum_i \sum_j x_i x_j r_{ij} s_i s_j = \sum x_i^2 s_i^2 + \sum_i \sum_j x_i x_j s_{ij} \quad (\text{i} \neq \text{j})$$

where s_i is the standard deviation of supply variation from source "i," x_i is the fraction of supply from source "i," and s_{ij} is the correlation between variations in supply from sources "i" and "j" (recall that $s_{ij} = r_{ij} s_i s_j$). If there is no correlation between supply changes by different suppliers (so that r_{ij} =0, for i$\neq$j), the second part of the above equation is zero and we are left with a simple extension of our original Herfindahl approach, which does not weight the fractions of supply by their individual uncertainties. As in the case of the diversification index H, the objective is to minimize the value of P, which now takes into account supplier-specific risk factors, and correlation between actions of suppliers.

We can take account of correlation between suppliers in two ways: by introducing correlation coefficients (e.g., r_{ij}) or simply by grouping suppliers according to their historical or projected behavior (e.g., OPEC). In our earlier discussion, we took account of correlation among groups of suppliers by treating them like a single supplier. However, it is important to test analytically to be certain that such an assumption is warranted.

To illustrate the modern portfolio approach, we can use monthly data for oil supply during the 1990-91 Gulf War, when Iraq invaded Kuwait and, in retreat, set fire to Kuwaiti oil facilities. Almost simultaneously, Iraqi oil production fell precipitously.
From these data we can calculate the variance in production for a number of countries, for the World as a whole, and also the correlation coefficients (and thus the covariance) for selected pairs of countries.

We begin with Table 5, which shows production for key exporters from January 1990 through December 1991. Also shown are the average production during this 24 month period, the standard deviation from this average, and the percent variation. As discussed earlier the variance is just the sum of the squares of the deviations of monthly production from the mean, or average, production for the 24 month period:

$$V = \frac{\sum_{month} (p_{month} - p_{avg.})^2}{24},$$

while the standard deviation is the square root of this sum. The latter can be expressed as an average percentage change in supply, relative to the average for the period.

Not surprisingly, the standard deviation for supply from Iraq during this period was 1.09, or 109 percent, and that from Kuwait was 125 percent. In contrast, the change for Nigeria was 4.2 percent and that for Saudi Arabia was 17.4 percent. Output from OPEC as a whole, for the two-year period, only varied by 3.7 percent, and that for the world varied even less, by 1.7 percent.

Table 6 shows the correlation coefficients r between production by pairs of suppliers. The correlation coefficient between Iraq and Kuwait was a positive 0.93, confirming that the reduction in supply by Kuwait was strongly correlated with the reduction in Iraqi output. In contrast, the correlation coefficients between Iraq and other suppliers are all strongly negative, close to minus one: between Iraq and Saudi Arabia the coefficient was -0.88, for Libya -0.85, and similarly for other suppliers. The same pattern applies to correlation between Kuwait and other OPEC suppliers.

Table 5
OIL PRODUCTION
Gulf War Period (1990-91)
(000 b/d)

	Iran	Iraq	Kuwait	Saudi Arabia	Libya	Nigeria	Venez	OPEC PROD	NON-OPEC PROD	WORL PROD
<u>1990</u>										
Jan	2,700	2,946	2,003	5,537	1,222	1,731	1,990	23,573	37,322	60,895
Feb	3,000	2,946	2,003	5,636	1,375	1,731	2,140	24,270	36,883	61,153
Mar	3,000	2,946	2,184	5,765	1,324	1,731	2,040	24,589	37,467	62,056
Apr	2,900	2,997	1,958	5,888	1,273	1,830	2,040	24,583	37,196	61,779
May	3,200	3,150	1,958	5,394	1,273	1,731	2,040	24,333	36,879	61,212
Jun	3,100	3,251	1,762	5,398	1,273	1,731	2,040	24,103	36,280	60,383
Jul	3,050	3,454	1,858	5,394	1,273	1,731	2,040	24,384	36,104	60,488
Aug	3,300	1,016	100	5,789	1,426	1,830	2,090	20,861	36,080	56,941
Sep	3,300	508	100	7,660	1,426	1,880	2,290	23,073	36,415	59,488
Oct	3,000	457	75	7,729	1,579	1,929	2,275	23,103	36,725	59,828
Nov	3,200	432	75	8,224	1,528	1,929	2,320	23,862	36,784	60,646
Dec	3,300	432	75	8,481	1,528	1,929	2,340	24,335	36,523	60,858
<u>1991</u>										
Jan	3,200	250	50	8,140	1,500	1,906	2,396	23,778	36,959	60,737
Feb	3,300	0	0	8,200	1,500	1,906	2,396	23,709	36,724	60,433
Mar	3,400	0	0	8,000	1,450	1,906	2,396	23,558	37,130	60,688
Apr	3,300	200	0	7,400	1,450	1,906	2,346	23,008	36,271	59,279
May	3,300	350	0	7,400	1,450	1,906	2,346	22,937	36,156	59,093
Jun	3,300	350	75	8,150	1,450	1,858	2,346	23,713	35,575	59,288
Jul	3,400	400	165	8,475	1,450	1,858	2,346	24,348	35,932	60,280
Aug	3,400	400	195	8,465	1,450	1,906	2,346	24,367	35,217	59,584
Sep	3,300	400	299	8,400	1,500	1,906	2,346	24,296	36,320	60,616
Oct	3,300	400	429	8,450	1,500	1,809	2,396	24,480	36,100	60,580
Nov	3,300	400	499	8,440	1,550	1,906	2,396	24,781	36,049	60,830
Dec	3,500	400	519	8,640	1,550	1,931	2,446	25,179	36,061	61,240
MEAN	3,210	1,170	683	7,294	1,429	1,851	2,256	23,88	36,46	60,349

(X)								4	5	
STDEV	186	1,281	853	1,270	104	78	153	876	556	1,053
STDEV/X	5.8%	109.5 %	125.0 %	17.4%	7.3%	4.2%	6.8%	3.7%	1.5%	1.7%

Table 6
Correlation Coefficients for Selected Suppliers
Gulf War (1990-1991)

	r_{ij}						
COUNTRY	Iran	Iraq	Kuwait	Saudi Arabia	Libya	Nigeria	Venezuela
Iran	1.00						
Iraq	-0.71	1.00					
Kuwait	-0.10	0.93	1.00				
Saudi Arabia	0.68	-0.88	-0.80	1.00			
Libya	0.62	-0.85	-0.81	0.84	1.00		
Nigeria	0.60	-0.87	-0.85	0.83	0.83	1.00	
Venezuela	0.74	-0.89	-0.82	0.92	0.85	0.81	1.00

In short, as production dropped in Kuwait and Iraq, other suppliers increased production to compensate for the loss of supply. Because of its high basic level of output, and strong negative correlation, Saudi Arabia played a major role in replacing production and exports from Kuwait and Iraq. In this particular crisis, then, a portfolio of supply from even a broad group of OPEC suppliers entailed little risk: strong negative correlation made the portfolio risk function relatively small. Of course, a portfolio dominated by supply from Iraq and Kuwait would have entailed very high variance and risk.

A similar analysis can be performed for the 1973-74 and 1978-79 oil crises. At least for the 1978-79 crisis, which was precipitated by the Iranian revolution, a similar result holds: a well diversified portfolio entailed little risk of physical supply disruption.

The relevant period to consider in this kind of security analysis should be chosen according to the policy time-frame of interest, as well as the ability of the world oil supply system and the ability of consuming countries to adapt to circumstances. For example, if other producers can increase output within six months, or if strategic stocks provide a six-month cushion, then one will be interested in the variance on a six month time horizon.

A comprehensive policy approach to the physical supply security should test the portfolio of supply against possible future disruption scenarios, subsequently adjusting the desired portfolio to minimize overall risk.

The dominant effect in each oil crisis was not the actual disruption of supply (at least for those consumers who were well-diversified) but rather a rapid rise in price in the months following the actual physical cutback. According to analysis done in 1983 (Neff, et al), the driving force for the price increase in the 1978-79 crisis was increased demand for inventories by major consuming nations. That is, the psychological effect of the crisis precipitated by the Iranian revolution was much more important than the physical effect. As demand rose, prices for oil products in end-use markets increased rapidly. Observing that "netback" prices (the implied value of a barrel of oil based on the products made from it) were much higher than producer government selling prices, producers changed their own pricing policies to a netback basis, so that profits otherwise going to oil companies and other intermediaries could be captured by exporting nations.

8. DOMESTIC VERSUS FOREIGN SOURCES OF SUPPLY

It is often thought that energy security can be increased by developing indigenous supply sources. According to our formulation, there are two ways in which domestic supply can affect risk. The first is the simple effect of adding an additional supplier, which increases diversification and reduces risk. An example might be adding domestic enrichment capacity in Japan, which is otherwise so dependent on the US.

The second is that domestic supply has the *potential* to have a lower level of intrinsic risk than foreign sources (i.e., lower variance). However, this is hardly automatic. For example, the US uses a great deal of domestically-mined coal, much of which is transported by rail. This supply is not totally certain: In the short-run, a rail labor strike could severely reduce access to this indigenous energy source; in the long-run, local environmental constraints or global agreements to reduce CO2 emissions, could also increase the risk of depending on this indigenous resource. Similar observations apply to the construction of domestic nuclear fuel cycle facilities or other efforts to avoid import dependence.

It is thus important to realize that there is an uncertainty about the amounts available even in the case of domestic supplies. That is, each domestic supply source has an implicit variance s^2, just as does an import source. The question in building a portfolio of supply that minimizes risk is simply a matter of determining the variances of domestic and international sources. There is no absolute distinction. The basic problem in all cases is to identify and quantify risk factors and then build a portfolio of supply that minimizes variance and thus risk.

9. MARKET, OR SYSTEMATIC, RISK

As examined in the preceding section, the way to reduce risks associated with individual suppliers of a given fuel or energy source is to diversify among suppliers, weighting dependence on individual suppliers by the historical or anticipated fluctuations in supply, the deviation or variance, so that the overall fuel portfolio risk is minimized. As was pointed out, this approach can virtually eliminate risks associated with individual suppliers, but it cannot eliminate systematic or overall market risk.

The overall market risk, say for oil or nuclear fuel, has been quite evident historically. In the case of nuclear fuel, the mid-1970s actions of the US—which held a monopoly on enrichment services—affected all consumers and led utilities to seek large amounts of natural uranium supplies to meet requirements of enrichment contracts entered into in panic. At about the same time, the 1974 Indian nuclear test led Canada to restrict exports of uranium. The net result was a reduction of supply and a surge in demand. A similar pattern has recurrently afflicted the oil market: a restriction of supply (however small) accompanied by a surge in demand (largely for inventories) by panicked consumers has led to substantial quantity and price fluctuations.

This situation is also common in the stock market where changes in general economic, political or other conditions often lead to systematic changes in market conditions: such conditions can make stock prices move up or down together. The degree to which a given stock reacts to such overall market changes is usually characterized by the parameter b . If the general level of the market changes, the price of an individual stock may move up or down according to the degree its price is correlated with the market as a whole. If s^2_{market} represents the variance of the market as a whole and s_{im} the covariance between stock "i" and the market, then

$$b_i = \frac{s_{im}}{s^2_{market}} .$$

That is, b_i is a measure of the contribution of the variance of stock "i" to the overall market variance.

In the case of the oil market, the overall market variance has been relatively small (if one supplier reduces output, others compensate; i.e., they are negatively correlated) but the variance for Iran, Iraq and a few other suppliers has been large. Without compensating increases in oil production, the high values of b for these countries would be responsible for much of the variance in the market as a whole.

This suggests a mechanism to reduce the market component of risk in the supply portfolio for a given country. Suppose we can choose from suppliers whose behavior is not significantly correlated with that of the market as a whole, and that there are enough of these suppliers that we can diversify adequately. Recalling our earlier portfolio variance equation and substituting b_i for s_{im}, we obtain

$$\begin{aligned} \mathrm{P} &= \sum_i \sum_j x_i x_j r_{ij} s_i s_j \\ &= \sum_i x_i \sum_j x_j s_{ij} \\ &= \sum_i x_i s_{im} \\ &= s^2_m \sum_i x_i b_i \end{aligned}$$

Where s^2_{market} is the variance in the market (e.g., the oil market) as a whole. Remembering that our objective is to minimize the portfolio variance "P," one way to do so is to pick suppliers that have values of b that are below the market average of one. That is, to adjust the fractions of supply x_i to favor sources with low or negative b''s.

We thus have a two-part process: pick suppliers that have low intrinsic variance, and which also have low correlation with the market as a whole—i.e., make little contribution to overall, or systematic, market risk.

In general, one does not want to do this when investing in the stock market since picking stocks with low intrinsic variance usually means lower return from such stocks, and low correlation with the overall market means that one's portfolio of investments will not rise with the stock market as a whole. In the case of the stock market, low risk means low returns; in the case of energy supply, low risk means energy security.

In addition to diversifying among fuels and supply sources and optimizing on low-variance sources to reduce overall risk, there are a number of mechanisms that may be employed to reduce exposure to overall, or systematic, market risk. We examine three mechanisms here: investment, contracting approaches, and inventories.

Investment Direct investment can, but does not always, increase security of supply from a foreign producer. In effect, one invests to narrow the variance (s^2) in potential supply. It can be more difficult for a producer to reduce supply to an equity partner. Japan and Korea have pursued this strategy in uranium procurements (but not in the less diversified downstream fuel processing steps such as enrichment). Moreover, the price of narrowing the risk has often been high. Japan was an early investor in Niger, which has turned out to be one of the highest cost suppliers of uranium, but not in Canada, which has the lowest-cost uranium in the world (Korea Electric has invested in Cigar Lake, the richest ore-body ever discovered). The right kind of investment in a Canadian mine can yield uranium whose price is close to record low production cost. Japanese firms have invested extensively in mining projects in Canada for copper, coal and other raw materials, but not for uranium.

In terms of our formalism above, direct investment can have two effects: reducing the variance of that source, and its correlation b with the overall market portfolio risk. That risk is, in effect, shifted to other consumers. As a result, a given consuming country can invest to reduce its overall portfolio risk "P."

Contracting A variation of this approach is to write long-term contracts with reliable (low variance) suppliers. Since the total amount of supply from a given supplier is relatively constant, the effect is to reduce the variance seen by the contracting consumer while increasing that seen by other buyers.

Even better is a long-term contract with consumer-dictated variability in the amount purchased. Uranium suppliers have been willing to write such contracts with little or no price premium. In the event of reduction of supply from one source, a consuming nation with contracts with upward flexibility can relatively quickly compensate for lost supply. The producer may hold inventories to hedge the risk of customer exercise of upward flexibility, or be forced to buy in the spot market at higher prices. In effect, the supply and price risk is shifted from the consumer to the supplier.

The effect on portfolio risk minimization is obvious: if an importer contracts with, or otherwise secures, uranium from a producer characterized by a high variance (perhaps because the price is low), the ability to vary off-take under a contract with a secure (low variance) producer can completely cancel the risk from the less secure supplier. Effectively, the fractions x_i of supply from individual suppliers can be adjusted to reduce portfolio risk. In principle, if a buyer can conclude contracts under which the variability of off-take is equal to the intrinsic variance due to riskier suppliers, then the overall portfolio variance or risk can be reduced to zero. This situation is analogous to the use of options in equity markets to hedge risk.

While options and futures markets do not exist for uranium, one can achieve the same result through contracting and investment mechanisms. In the case of oil, buyers do have access to futures and options contracts. While these may not significantly affect physical supply in crisis, they can greatly reduce the economic consequences of disruption of supply. Thus a mix of physical contracting and financial instruments can greatly reduce vulnerability for import-dependent nations.

Inventories The third mechanism—holding inventories—is usually the first one mentioned, but also the most expensive to pursue. A strategic stockpile is like having access to an additional supplier, one characterized by low variance or risk of availability. Indeed, because the stockpile would only be drawn down in the case of a shortfall in world market supply, the inventory source has a b of -1. The effect on the importer's portfolio risk is evident: if a supplier "i" defaults and does not deliver, its contribution to the portfolio risk can be replaced with a much more favorable contribution. In the last equation above, the failing supplier contribution to market risk is $x_i b_i$. A consumer with a strategic stockpile can replace this with a similar fraction of supply x_i with a b of minus one. The consuming nation can thus hedge both intrinsic risk associated with individual suppliers and overall market risk by use of strategic stockpiles.

However, the cost of "production" from a stockpile is much higher than from other sources. When the stockpile is built, one has to pay the market price for fuel above ground. If one invests in a mining or oil development project one pays just the cost of reserves, a much lower figure, and pays the cost of production (a much larger cost) close to the time of consumption. Moreover, one must build inventories well before a crisis, the timing of which is intrinsically uncertain, and pay substantial carrying costs on the original investment.

This said, there is considerable difference among fuels in the cost of holding inventories, as well as in the physical feasibility of doing so. The cost of holding natural uranium to generate a given amount of electricity is about three percent of the cost of holding oil to generate the same amount of electricity. If one were to stockpile low-enriched uranium, ready to be fabricated into fuel, the cost of stockpiling fuel would be about eight percent that of oil. The cost of holding coal for electricity generation is intermediate between that for nuclear fuel and oil. The net result is that hedging risks with physical inventories is much less expensive for uranium and nuclear fuel than it is for oil or coal.