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Abstract. Along with the oil price, concerns about the security of energy supply have soared once again in recent years. Yet, some 40 years after the OPEC oil embargo in 1973, there is no widely accepted statistical measure that captures the notion of energy security. Most likely, this deficit is the result of the great variety of resource economic aspects that are of potential relevance. This paper develops a statistical risk indicator that aims at characterizing the physical energy supply vulnerability of nations that are heavily dependent on energy imports. Our risk indicator condenses the empirical information on the imports of the whole range of fossil fuels, originating from a multitude of export countries, as well as data on their indigenous contribution to domestic energy supply, into a single figure. Applying the proposed concept to empirical energy data on Germany and the U.S. (1980-2007), we find that there is a large gap in the supply risks between both countries, with Germany suffering much more from a tight energy supply situation today than the U.S.

JEL classification: C43, Q41.

Key words: HERFINDAHL Index, SHANNON-WIENER Index, Energy Supply Risk.

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1 Introduction

Some 40 years after the OPEC oil embargo in 1973, there is still no widely accepted statistical measure of energy security (LÖSCHEL et al., 2010:1665). Most likely, this deficit is the result of the great variety of resource economic concepts, such as absolute and relative scarcity, that are of potential relevance.[1] In fact, given the multitude of facets of the notion of energy security, including physical, economic, social and environmental dimensions (CONSTANTINI et al. 2007:210), it appears to be hardly possible to integrate all of them into a single indicator.

Virtually all measures developed so far therefore concentrate on particular aspects of energy security. Basically, these aspects can be divided along two dimensions (GRUBB et al. 2006:4051): (i) dependence or vulnerability measures and (ii) physical versus economic indicators, a categorization that is by no means beyond controversy. Physical measures reflect the relative level of imports or prospects for shortages and disruptions, whilst economic measures describe the cost of fuels and energy supply or prospects for price shocks. While vulnerability refers to an economy's entire exposure to energy supply shocks or price spikes, dependence relates to an economy's reliance on a particular fuel source.

In accordance with the multi-dimensionality of the notion of energy security, numerous contributions to the literature have developed and employed quantitative measures to capture diverse resource economic aspects, with BLUM and LEGEY (2012), JANSEN and SEEBREGTS (2010), LÖSCHEL et al. (2010), LEFÈVRE (2010, 2007), LE COQ and PALTSEVA (2009), FRONDEL and SCHMIDT (2008), SCHEEPERS et al. (2006, 2007), GRUBB et al. (2006), CONSTANTINI et al. (2007), NEUMANN (2007, 2004), and JANSEN et al. (2004) being among the most recent studies. While we find the work of JANSEN et al. (2004) particularly inspiring, the present article suggests an alternative concept that is based on HERFINDAHL's (1950) concentration index, rather than SHANNON's (1948) diversity measure, thereby conceiving a risk indicator instead of a measure of supply

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[1] While the notion of absolute scarcity focuses on the potential exhaustion of resources such as oil or gas, relative scarcity denotes transient resource shortages, for instance due to missing supply capacities.

security, as will become transparent from our discussion below.

While taking account of all energy sources used in a country, both renewable and non-renewable, the basic ingredients of our measure are (1) a country's own contribution to the total domestic supply of any fuel, (2) the fuels' import shares, and (3) the probabilities of supply disruptions in export countries. With its focus on the aspect of relative scarcity,[2] our measure's empirical outcome is a single figure that characterizes a country's total risk of physical shortages originating from its reliance on fossil fuel imports. Ignoring both resource prices and their volatility, this statistical indicator aims at quantifying the long-term energy supply risk, with its values reflecting potential (risk-weighted) fossil fuel import losses, albeit not their economic consequences. In other words, our measure may be classified as an indicator of resource vulnerability or physical (un-)availability.

The risk of physical unavailability is, as LEFÈVRE (2010:1636) points out, of major concern wherever prices do not reflect the demand and supply situation in a market, most notably, if prices are the result of a regulated, rather than a competitive market setting.[3] Specifically, our measure may be particularly well-suited if the supply is constrained by infrastructure, such as a natural gas pipeline. In that case, a country's supply reduction, such as Russia's temporary gas supply interruptions both at the beginning of 2006 and 2009, could translate into actual shortages, rather than price increases. In contrast, this measure may provide for a poor picture of reality when supply is flexible and relatively homogeneous, as in the case of petroleum.

Furthermore, unlike the Supply-Demand Index proposed by SCHEEPERS et al. (2006, 2007), our approach does not account for demand reductions, but follows

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[2] The focus on relative scarcity is due to the fact that the eventual exhaustion of energy resources, such as oil and gas, is not yet imminent (GORDON 2005:122-123). In a similar vein, more recent contributions to the resource economics literature than GRAY (1914) and HOTELLING (1931), such as ADELMAN (1990, 1993) and GORDON (1967), are based on the assumption that the exhaustion of resources does not bear any binding restriction.

[3] Although there may be a myriad of causes for welfare losses resulting from frictions in the energy markets, according to LEFÈVRE (2010:1635), none appears to be as pervasive and politicized as physical unavailability that is due to fossil fuel concentration.

conventional tacks that take the demand for energy as exogenously given, thereby focusing on the supply side. Therefore, our indicator does not provide for any answers on the effects of raising energy taxes, nor on many other issues. Not least, our measure ignores the issue of fungibility, that is, the ease of switching between suppliers and supply alternatives in case of supply disruptions. Natural gas supplied via pipeline, for instance, is less substitutable in the short-run than Liquified Natural Gas (LNG) that is delivered by tank ships. We believe, though, that the issue of fungibility is primarily relevant in the short-run, but not in the long-term. These limitations should be borne in mind when interpreting the values resulting from our indicator.

The following section elaborates on our statistical indicator characterizing the long-term primary energy supply risk of a country. In Section 3, the proposed concept is applied to empirical energy data on Germany and the U.S. This choice is motivated by the fact that the U.S. is a country with rich natural resources, whereas Germany is heavily dependent on oil and gas imports. The last section summarizes and concludes.

2 A Measure of the Physical Energy Supply Risk

To address the issue of substitution between fuel types, in line with LE COQ and PALTSEVA (2009), we first conceive a fuel-specific indicator that characterizes the long-term physical supply risk for each type of fossil fuel. In fact, an important feature of our aggregate risk indicator is that it is a weighted average of fuel-specific risks. The weights are the relative contributions of a fuel to the overall primary energy supply of a country, including domestically produced fossil fuels, as well as bio-fuels and electricity and heat generation from renewables.

In a similar vein, the specific risks are weighted averages of both the import shares from foreign countries and the indigenous contribution to domestic supply, with the weights consisting of the product of the countries' relative supply levels and country-specific risks. This approach distinguishes our work from many other studies that propose an aggregate index alone. Indeed, the empirical example presented in Section 3 strongly motivates the use of fuel-specific risk indicators, as, above all, Germany's exposure to supply risks varies notably across fuel types.

2.1 A Fuel-Specific Risk Indicator

Denoting the risk probability of supply disruptions in export country j by r_j, where $0 \leq r_j \leq 1$, and given the choice between two concentration indices, we focus on HERFINDAHL's index (see Appendix A for a justification) and suggest the following quadratic form as a measure to capture a nation's supply risk related to fuel f:

$$\text{risk}_f := \mathbf{x}_f^T \cdot \mathbf{R} \cdot \mathbf{x}_f = x_{fd}^2 \cdot r_d + \sum_{j=1}^{J} x_{fj}^2 \cdot r_j. \tag{1}$$

A similar definition is suggested by LEFÈVRE (2007:56), although he omits the indigenous contribution x_{fd} to the domestic supply of fuel f. Matrix $\mathbf{R}$, which can be designated as risk matrix, is defined by $\mathbf{R} := \sqrt{\mathbf{r}} \cdot \mathbf{I} \cdot (\sqrt{\mathbf{r}})^T$, where $\mathbf{I}$ is the identity matrix and $\mathbf{r}^T := (r_d, r_1, ..., r_j, ..., r_J)$ may be denoted as risk vector. It seems natural for import countries, such as Germany, to set the probability of a long-term disruption of a nation's own contribution to its domestic supply to zero: $r_d = 0$, notwithstanding potential transient short-term supply disruptions. A non-zero probability of domestic supply disruptions, though, can be easily accommodated in this framework by allowing r_d to deviate from zero, thereby treating the import country in the same way as any other fuel-providing export country.

From the perspective of an import country, the components of share vector $\mathbf{x}_f$, defined by $\mathbf{x}_f^T := (x_{fd}, x_{f1}, ..., x_{fj}, ..., x_{fJ})$, are the primary instruments to improve supply security. In the polar case of perfect security in which the supply of fuel f is solely satisfied by perfectly secure countries, a situation characterized by $\mathbf{r} = \mathbf{0}$, the supply risk related to fuel f, as defined by (1), takes on the minimum value of zero. In the opposite polar case in which the total supply of fuel f exclusively originates from a single highly instable export country j such that $r_j = 1$, risk_f takes on the maximum value of unity. In short, the fuel-specific risk defined by (1) is normalized: $0 \leq \text{risk}_f \leq 1$ (for a proof of this proposition, as well as other interesting properties of this indicator, see Appendix B).

To sum up, definition (1) comprises three major aspects of energy security: (1) a country's own contribution x_{fd} to the total domestic supply of fuel f, (2) the political and economic stability of export countries as captured by risk vector $\mathbf{r}$, and (3) the diversification of imports as reflected by vector $\mathbf{x}_f$. The role of diversification is incorporated in the fuel-specific indicator risk_f by building on HERFINDAHL's index, which is known in ecology as SIMPSON diversity index (STIRLING, 1999). Increasing the indigenous contribution x_{fd} decreases the contribution x_{fj} of export country j to the total domestic supply of fuel i, thereby alleviating the import dependency with respect to fuel f and, hence, risk_f. This obvious effect can be seen from the following relationship:

$$x_{fj} = s_{fj}(1 - x_{fd}) \quad \text{for} \quad j = 1, ..., J, \tag{2}$$

where s_{fj} denotes the share of export country j in total imports of fuel f.

Finally, if $\mathbf{R}$ is defined by $\mathbf{R} := \sqrt{\mathbf{r}} \cdot \mathbf{I} \cdot (\sqrt{\mathbf{r}})^T$, a tacit assumption underlying risk definition (1) is that supply disruptions are uncorrelated among export countries. To take account of cartels of export countries, such as the OPEC cartel, the risk matrix $\mathbf{R}$ must be slightly amended as follows:

$$\mathbf{R}_c := \begin{pmatrix} r_d & 0 & 0 & . & . & . & 0 \\ 0 & r_1 & 0 & . & . & . & 0 \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & r_c & . & r_c \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & r_c & . & r_c \end{pmatrix}, \tag{3}$$

where the cartel discipline is characterized by a common disruption probability r_c. The bloc in the south-east of matrix $\mathbf{R}_c$ reflects the correlation of supply disruptions among cartel member countries. In effect, this amendment amounts to treating all cartel members as a single country, whose share is the sum of the members' individual contributions x_{fj}.

The assumption underlying $\mathbf{R}_c$ implies that the supplies from all cartel members are concerned even when the supply of only two of them is actually disrupted, as was the case in the Iran-Iraq war (1979-1980). As a result, in our empirical example presented in Section 3, the risk values obtained for the OPEC cartel case can be expected to be larger than the true risks. It is straightforward, however, to avoid this overestimation: For the case of the Iran-Iraq war, for example, the south-east bloc of $\mathbf{R}_c$ may be reduced to a 2 x 2 sub-matrix with common risk r_I, while all the other OPEC cartel members are treated like any other export country:

$$\mathbf{R}_I := \begin{pmatrix} r_d & 0 & 0 & . & . & . & . & 0 \\ 0 & r_1 & 0 & 0 & . & . & . & 0 \\ . & . & . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & . & r_{J-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & . & 0 & r_I & r_I \\ 0 & 0 & 0 & 0 & . & 0 & r_I & r_I \end{pmatrix}. \qquad (4)$$

In short, it bears no fundamental difficulty to integrate the case of supply disruptions in which several export countries are involved into our concept.

2.2 Overall Risk Indicator

To measure a nation's entire vulnerability with respect to all kinds of fuel imports, we suggest evaluating the following generalization of the fuel-specific supply risk defined by (1):

$$\text{risk} := \mathbf{w}^T \cdot \mathbf{X}^T \cdot \mathbf{R} \cdot \mathbf{X} \cdot \mathbf{w} = \mathbf{w}^T \cdot \mathbf{\Pi} \cdot \mathbf{w}, \qquad (5)$$

where $\mathbf{w}^T := (w_1, ..., w_f, ..., w_F)$ represents a vector whose non-negative components w_f reflect the shares of the various fuels and energy sources in a nation's total energy consumption and, hence, add to unity: $w_1 + ... + w_F = 1$. The columns of matrix $\mathbf{X}$ comprise the indigenous as well as the export country's contributions to the domestic supply of each of the F fuels and energy sources:

$$\mathbf{X} := \begin{pmatrix} x_{1d} & . & x_{fd} & . & x_{Fd} \\ x_{11} & . & x_{f1} & . & x_{F1} \\ . & . & . & . & . \\ x_{1j} & & x_{fj} & & x_{Fj} \\ . & . & . & . & . \\ x_{1J} & . & x_{fJ} & . & x_{FJ} \end{pmatrix} = (\mathbf{x}_1 \, ... \, \mathbf{x}_F). \qquad (6)$$

The diagonal elements π_{ff} of the product matrix $\mathbf{\Pi} := \mathbf{X}^T \cdot \mathbf{R} \cdot \mathbf{X}$ are identical to the fuel-specific supply risks: $\pi_{ff} = \text{risk}_f = x^2_{fd} \cdot r_d + \sum_j^J x^2_{fj} \cdot r_j \geq 0$. Generally, non-vanishing off-diagonal elements

$$\pi_{f_1 f_2} = x_{f_1 d} \cdot x_{f_2 d} \cdot r_d + \sum_j^J x_{f_1 j} \cdot x_{f_2 j} \cdot r_j > 0, \quad \text{where} \quad f_1, f_2 = 1, ..., F, f_1 \neq f_2, \tag{7}$$

take account of the fact that, for instance, oil supply disruptions in an export country may be correlated with those of gas. This seems to be highly relevant, as today Western nations are exposed to multiple risks of supply disruptions, such as simultaneous shortages of oil and gas: Iran, for example, is among the most important oil and gas producing countries, providing for the risk of serious oil as well as gas supply shortages in case of political conflicts.

Note that in the cartel case $\mathbf{R}_c$, both π_{ff} and $\pi_{\pi_{f_1 f_2}}$, comprise more non-zero elements than in the case in which risk matrix $\mathbf{R}$ is diagonal. As a result, the values of our total risk indicator are generally higher for $\mathbf{R}_c$ than for $\mathbf{R}$. Taking the Iran-Iraq example with matrix $\mathbf{R}_I$ given by (4) as an illustration, the off-diagonal elements read as follows:

$$\pi_{f_1 f_2} = x_{f_1 d} \cdot x_{f_2 d} \cdot r_d + (x_{f_1 (J-1)} + x_{f_1 J})(x_{f_2 (J-1)} + x_{f_2 J}) \cdot r_I + \sum_j^{J-2} x_{f_1 j} \cdot x_{f_2 j} \cdot r_j. \tag{8}$$

From this expression, it can be seen that $\pi_{f_1 f_2}$ is larger than the risk value given by (7) in case of a diagonal risk matrix $\mathbf{R}$. It also follows from expression (8) that employing matrix $\mathbf{R}_I$ amounts to treating both countries $J-1$ and J as a single country with risk common risk r_I. Finally, it bears noting that the total supply risk (5) is normalized, as is intuitive and proved in Appendix B: $0 \leq \text{risk} \leq 1$.

3 Empirical Application

Based on energy data provided by the International Energy Agency (IEA), we now employ both the fuel-specific as well as the overall supply risk indicators to compare the inter-temporal changes in the energy supply risks of Germany and the U.S. during the period 1980 through 2007, as well as their prospects for 2020. The range of the period 1980-2007 allows us to examine both country's reactions to the oil price shocks of the 1970s, where the first can be traced to the OPEC oil embargo in 1973, while the second shock was the result of the Iranian Revolution in 1979 and the subsequent war between Iran and Iraq in 1980.

The probabilities r_j of supply disruptions in individual export countries are identified here primarily by applying the OECD (2008) system used for assessing country credit risks, where countries are classified into eight risk categories (0-7), with 7 standing for the highest risk category. Examples of these country-specific classifications, which we have re-scaled to lie within the range of zero to unity, are displayed in Table C1 of Appendix C. Although commonly used to gauge loan loss risks, these classifications should also satisfactorily characterize a country's political and economic situation, as political risks and other risk factors are integrated into the OECD assessment as well.

These classifications are assumed here to be inter-temporally constant, an assumption that turns out to be inconsequential, as the classification of an individual country hardly changes over time. Alternatively using the contemporaneous classification of each country leaves our results virtually unaltered. To further check the robustness of our results, we additionally apply the country classifications provided by the World Bank (2008). The comparison of the OECD and World Bank assessments provided in Appendix C indicates that the alternative classifications are quite similar for the majority of countries.

Starting with oil, the most important fossil fuel both in Germany and the U.S. (Table 1), we find that both country's supply risk roughly doubled – in terms of our fuel-specific indicator – between 1980 and 2007, implying a substantially increasing gap (Figure 1). A major reason for this finding is that Germany's reliance on Russian oil has risen dramatically since the end of the 1970s. At present, Russia is, by far, Germany's most important oil provider, being responsible for as much as about 40% of total oil supply. Actually, Germany suffers much more from today's tight oil supply situation than the U.S. This is due to the fact that the substantial decline in U.S. oil production to only a third of the domestic supply has been almost outweighed by intensified imports from stable countries such as Canada.[4]

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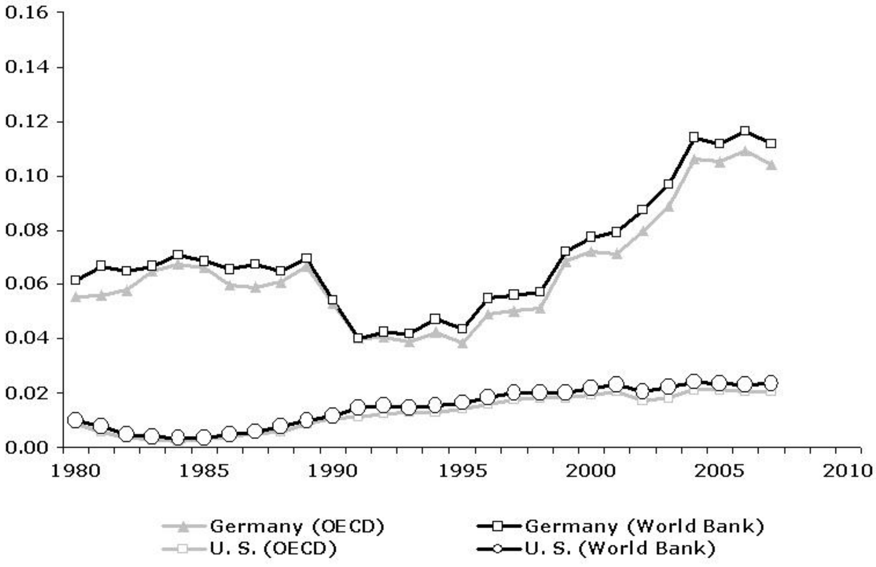
[4] Note that using World Bank country classifications instead of those of the OECD virtually leads to the same conclusions, with the results for the U.S. being identical (Figure 1). This also holds true for the

Table 1: **Primary Energy Supply Mix in Germany and the U.S.**

	U. S.						Germany					
	1980	1990	2000	2004	2007	2020	1980	1990	2000	2004	2007	2020
Oil	44.4	40.0	38.7	40.7	39.3	39.3	40.8	35.3	38.3	35.9	33.9	35.5
Hard Coal	20.0	22.5	22.6	22.5	22.4	21.4	17.5	15.5	13.4	12.7	14.3	13.0
Gas	26.3	22.8	23.8	22.1	22.9	21.5	14.2	15.4	20.9	22.6	22.5	22.8
Nuclear	3.8	8.3	9.0	9.1	9.2	9.1	4.0	11.2	12.9	12.5	11.1	2.0
Brown Coal	0.8	1.3	1.0	1.0	1.0	1.0	21.7	20.6	11.3	11.9	11.6	10.7
Other sources	4.7	5.1	4.9	4.6	5.2	7.7	1.8	2.0	3.2	4.4	6.6	16.0

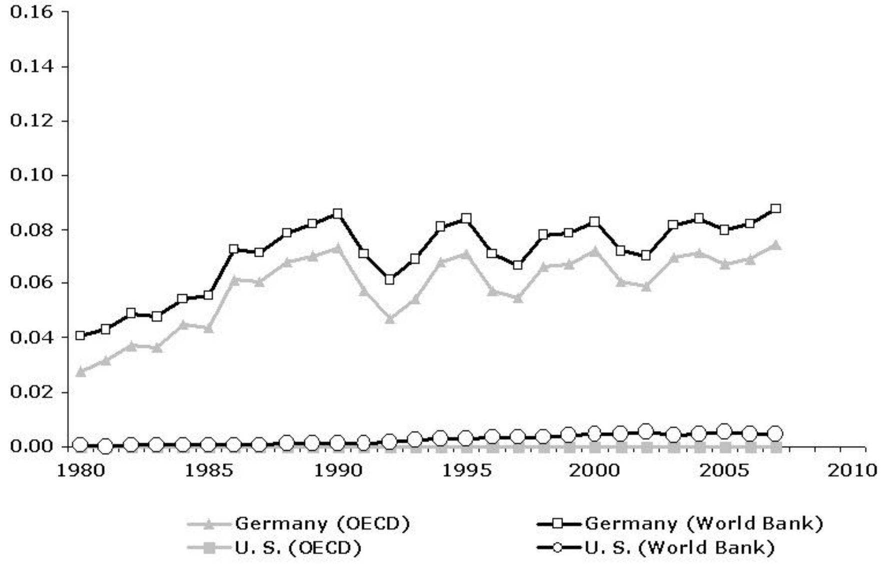
Note: Shares for 1980 through 2007 are based on IEA (2004d, 2006c, 2006d, 2008), shares for 2020 rest on IEA (2007) for the U.S. and on IER, RWI, ZEW (2010) for Germany. Other sources include hydro, solar, tide, wind power, etc.

Figure 1: **Crude Oil Supply Risks in Germany and the U.S. (1980-2007)**



A pattern similar to that for oil can be observed for both country's natural gas supply risks (Figure 2). While the moderate reduction of the indigenous share in U. S. gas supply has been balanced by extending the imports from Canada, in the end stabilizing the U. S. gas supply risk at the negligible level of the 1980s, the drastic decline of Germany's relative own contribution to its domestic gas supply has been countered by surging gas imports from Russia. Today, the contribution of Russian pipelines to Germany's gas supply amounts to about 37% and, hence, is almost as high as Russia's oil supply share. By contrast, Russian gas played only a minor role for Germany in the 1970s. Note also that Germany's gas-specific risk closely follows the alterations in the import shares from Russia and that the gas-specific risk is entirely due to the Russian imports, as the country risks of Norway and the Netherlands, Germany's remaining gas providers, are vanishing. Russia's dominance in both the German oil and gas procurement are all the more disconcerting as the significance of gas has substantially risen. The share of gas in Germany's primary energy supply mix increased from 14.2% in 1980 to 22.5% in 2007 (Table 1).[5]

Figure 2: **Natural Gas Supply Risks in Germany and the U.S. (1980-2007)**



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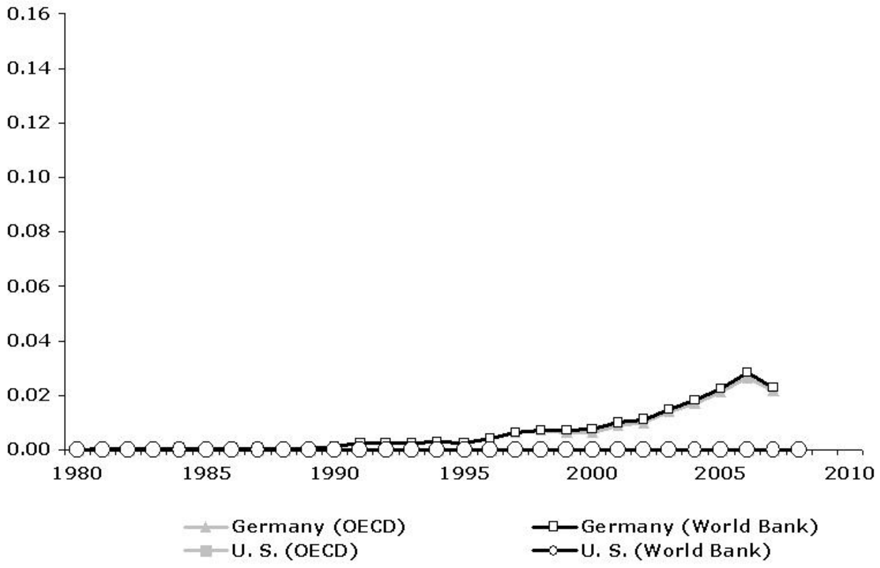
supply risk of hard coal (Figure 3) and the total supply risk (Figure 4).

[5] With particular respect to the different kinds of risk classification, we observe slightly stronger differences for the gas supply risks than for those of oil. The major reason for the higher level is the larger risk attributed to Russia by the World Bank indicators (Table C1).

In contrast to gas, for which consumption as well as imports have been growing since the 1970s, Germany's abundantly available brown coal has lost relative significance. Its share in the primary energy supply mix shrank from 21.7% in 1980 to 11.6% in 2007 (Table 1). Another domestic energy source, German hard coal, experienced a decline due to the widening gap between domestic production cost and world market prices of coal (FRONDEL et al. 2007). Yet, despite its substantial and increasing economic disadvantages, the indigenous contribution to overall hard coal supply in Germany merely decreased from about 85% in 1980 to some 33% in 2007, so that the rise of the specific supply risk was quite moderate (Figure 3). By contrast, renewable energy technologies such as wind, solar, and hydro power are still of minor importance for supply security.

While this also holds true for the U.S., there is hardly any reliance on foreign hard coal, which, aside from oil and gas, is the most important fuel (Table 1). It is not surprising, therefore, that the risk of hard coal supply virtually vanishes for the U.S. (Figure 3). In short, with the increase in nuclear power, which has partially compensated the declining share of domestic oil in the U.S. primary energy supply since the 1980s, and a very low dependence on gas and hard coal imports from instable countries, the U.S. energy security situation appears to be much better than that of Germany.

Figure 3: **Hard Coal Supply Risks in Germany and the U. S. (1980-2007)**



This qualitative conclusion is substantiated by the calculation of the proposed total supply risk indicator, whose inter-temporal changes are displayed in Figure 4. In terms of our overall risk indicator, Germany's energy supply risk appears to be substantially higher than the U.S. risk. While it roughly doubled between 1980 and 2007 in the U.S., above all due to the doubling of the oil-specific supply risk in this period, the total supply risk almost tripled in Germany.

In addition to the increase in the oil-specific supply risk, the major reason for this development is the growing dependency from hard coal and, most notably, gas imports. This gap is likely to rise further within the next decades: In addition to the future decline of German hard coal production, with the end of subsidies being legally stipulated for 2018, the phase-out decision on nuclear power of 2011 implies that this energy source disappears from Germany's primary energy mix until 2022 (Table 1).[6] As a consequence, our indicator points to a further increase in Germany's energy supply risk,[7] whereas the U.S. risk may decline if the forecasts of the IEA (2007) on the primary energy supply mix for 2020 become true (Table 1). Actually, the recent decrease in both U.S. oil and gas imports due to the rise in the domestic production from shale and oil gas corroborates the expectation that U.S. energy supply risk may even approach zero until 2020.

The inter-temporal picture appears to be somewhat different (Figure 5) if the OPEC cartel is taken into account in calculating total supply risks and all OPEC members are uniformly characterized as highly instable countries, building a single block of oil exporters. Attributing the maximum risk of $r_c = 1$ to all OPEC members indicates that Germany heavily relied on OPEC oil in 1980. Yet, as well as the U.S., Germany has

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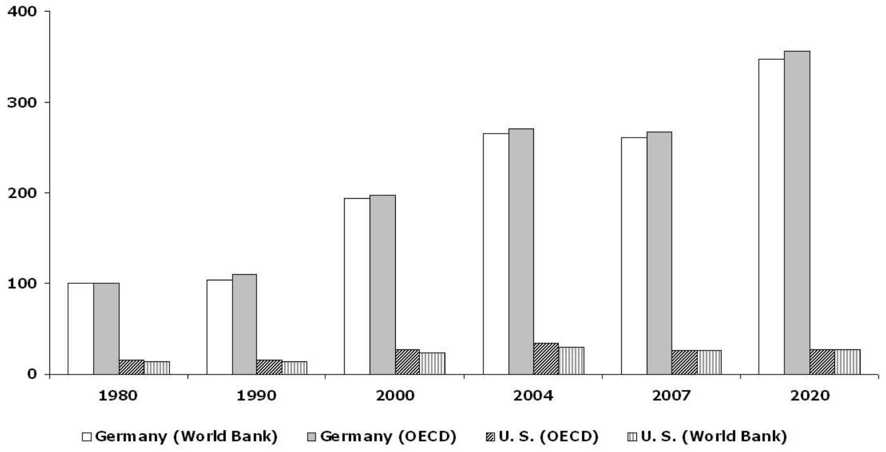
[6] Note that our calculations are based on the assumption that nuclear power should be treated as a domestic resource. The basis for this treatment is the fact that nuclear fuels are frequently imported in times when prices are low and stored up to several decades before used in nuclear power plants. This treatment of nuclear fuels as quasi-domestic energy source is also the prevailing practice in international energy statistics.

[7] The oil import shares for 2020 are assumed to be the same as in 2007, whereas we have presumed that the vanishing contribution of German hard coal may be replaced by increases in imports from Russia. Similarly, gas imports from Russia can be expected to rise as well, most notably due to the recent establishment of the off-shore pipeline in the Baltic sea that directly conveys gas from Russia to Germany.

Figure 4: **Total Energy Supply Risks in Germany and the U. S. (1980-2007)**



Note: All values refer to the situation in Germany in 1980 (1980:100).

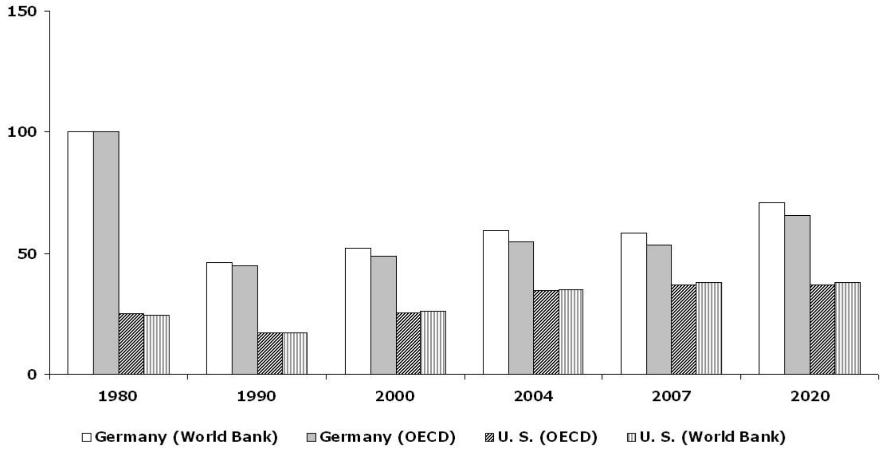
managed to reduce this dependency substantially in the aftermath of the oil crises.

Since 1990, however, U.S. energy risk has again increased, because the relative significance of U.S. oil production has shrunk dramatically until recently. In contrast, the energy risk remained quite stable in Germany between 1990 and 2007, most notably because the OPEC's oil supply share decreased from about 40% to less than 20%, whereas Germany's reliance on Russian oil imports has almost doubled, to some 40% in 2007. Given the significantly different values for U.S. risk when the OPEC cartel is taken into account, it bears noting again that in this case the risk values can be expected to overestimate the true risks (see Section 2).

4 Summary and Conclusion

In recent decades, numerous developing countries, most notably China, experienced strong economic growth, requiring more and more mineral and energy resources. As a consequence, industrialized countries are increasingly struggling to ensure the security of their energy and resource requirements, leading, for instance, to a strong support for domestically produced bio-fuels in the U.S. Yet, some 40 years after the OPEC oil embargo in 1973, there is no widely accepted statistical measure of energy security. This

Figure 5: **Total Energy Supply Risks in Case of a Strict OPEC Cartel Discipline**



Note: All values refer to the situation in Germany in 1980 (1980:100).

is all the more disconcerting given the strong case to explore the long-term evolution of energy supply security for policy design purposes (JANSEN, SEEBREGTS, 2010:1655).

This paper has conceived a statistical indicator for measuring the long-term primary energy supply risk of a country. While neglecting fuel prices and their volatility, but instead focusing on the physical availability of fossil fuels, our indicator includes four major aspects of long-term supply security: (1) diversification of sources in energy supply, (2) diversification of fuel imports, (3) long-term political and economic stability of export countries, and (4) a country's own contribution to its domestic energy supply.

In the terminology of LÖSCHEL et al. (2010:1668), who distinguish between ex-post and ex-ante indicators, our concept is an ex-ante indicator that addresses the issue of whether one may expect major welfare losses due to future frictions in a country's energy markets. There may have been circumstances, however, in which the actual supply risk had not changed at all over some time interval in the past, even when our ex-ante indicator would have pointed to a drastic increase in the supply risk over that interval. This exemplifies that our concept is not an appropriate ex-post indicator, which according to LÖSCHEL et al. (2010:1668) should attempt to answer the question of whether the energy markets caused a major economic friction in the past.

Applying the proposed long-term supply risk indicator to empirical energy data on Germany and the U.S. (1980-2007), we find that there is a large gap in the energy supply risk between both countries, with Germany suffering much more from the tight energy supply situation today than the U.S. This gap is likely to rise much further within the next decades: Given the nuclear phase-out decision of 2011 that implies the end of nuclear power in Germany by 2022, and the legislated dismantling of the hard coal subsidies by 2018, our calculations show that Germany's energy supply risk can be expected to rise even if the national goal of a 35% share of electricity production from renewable energies will be reached in 2020.

Appendix A: Candidate Indices

Our concept strongly relies on the notion of diversity, which itself comprises of at least three subordinate properties: variety, balance, and disparity (STIRLING, 1999:39-40). In our context, *variety* refers to the *number* of energy sources, including fuel categories such as hard and brown coal, gas, and oil, as well as the *number* of energy technologies such as nuclear, solar, and wind power that contribute to the overall energy supply of a country. Not least, the variety of import sources of fossil fuels is at issue. *Balance* refers here to the evenness of the discrete distribution of the shares of export countries in total imports of a fuel, as well as the evenness of the contributions of diverse fuels and energy technologies to a nation's primary energy mix.

Disparity, finally, refers in this case to the differences in the *characteristics* of diverse energy sources and technologies. For example, electricity production from hard and brown coal are less disparate in terms of short-term supply security than the electricity generation from wind and solar power, which is well-known to be volatile. While disparity is generally hard to quantify, this aspect appears to be of minor relevance for any measure of the long-term energy supply risk. Therefore, our concept focuses on the properties of variety and balance alone.

There are two prominent indices marrying variety to balance (JANSEN et al. 2004:18): The first is HERFINDAHL's (1950) concentration index,

$$H := \sum_{k=1}^{K} a_k^2, \tag{9}$$

where in our context a_k may reflect the shares in a variety of fuels and energy sources employed for satisfying a nation's total energy consumption. Alternatively, a_k may stand for the contributions of diverse export countries to the domestic supply of a fossil fuel.

Second, there is SHANNON's (1948) measure of entropy, frequently called SHANNON-WIENER index:

$$S := -\sum_{k=1}^{K} a_k \cdot \ln a_k. \tag{10}$$

Roughly speaking, both measures are of inverse character: While HERFINDAHL's index

H is a concentration measure, which is also known as HERFINDAHL-HIRSCHMANN index and used to assist the U. S. Federal Trade Commission in the assessment of horizontal mergers (FTC, 1992), the SHANNON-WIENER index S is an indicator of evenness. Accordingly, H takes on its maximum value of unity for the most unequal distribution, such as $a_1 = 1, a_2 = 0, ..., a_K = 0$, whereas S adopts its lowest value of zero in this polar case of highest concentration. On the other hand, for the opposite polar case of a perfectly even distribution, $a_1 = a_2 = ... = a_K = 1/K$, which displays the lowest concentration given a fixed number K of alternatives, H takes on its minimum value of $1/K > 0$, whereas S equals its maximum of $\ln K$, with both extreme values depending upon the number K of alternatives. Since the range of values of both indices is determined by these two opposite polar cases, H is restricted to values lying in the interval $[1/K, 1]$, while those of S fall within the range of $[0, \ln K]$.

Hence, S is not normalized in the sense that its concrete values lie within the interval of $[0, 1]$. In contrast, H is normalized, as $[1/K, 1] \subset [0, 1]$. This is a particularly desirable property that facilitates international and inter-temporal comparisons, as in practice one would like to know whether there are benchmarks in the form of fixed minimum and maximum values. S, on the other hand, is not limited, but logarithmically increases with K.[8]

Given the choice between these two indices, we deliberately base our energy supply risk indicator on HERFINDAHL's index, as it is better suited to reflect the risks associated with non-diversified energy portfolios than the SHANNON-WIENER index (LE COQ, PALTSEVA, 2009:4475). This is due to the fact that the SHANNON-WIENER index puts relatively more weight on small market participants, whereas HERFINDAHL's index places more emphasis on larger suppliers that may cause serious security problems.

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[8] By means of modification, JANSEN et al. (2004) demonstrate that S can be readily normalized into a [0,1] scale.

Appendix B: Properties of our Risk Indicator

Proposition I: The fuel-specific supply risk, given by

$$\text{risk}_f = x_{fd}^2 \cdot r_d + \sum_{j=1}^{J} x_{fj}^2 r_j,$$

is normalized: $0 \leq \text{risk}_f \leq 1$.

Proof of Proposition I: The fuel-specific risk_f is non-negative because it is a sum of non-negative risk elements r_f multiplied by squared, and thus also non-negative, weights x_{ij}. That risk_f is lower or equal than unity follows from $r_j \leq 1$, $r_d \leq 1$, $x_{fj}^2 \leq x_{fj}$ for $0 \leq x_{fj} \leq 1$, $x_{fd}^2 \leq x_{fd}$ for $0 \leq x_{fd} \leq 1$:

$$x_{fd}^2 \cdot r_d + \sum_{j=1}^{J} x_{fj}^2 r_j \leq x_{fd}^2 + \sum_{j=1}^{J} x_{fj}^2 \leq x_{fd} + \sum_{j=1}^{J} x_{fj} = 1.$$

Proposition II: The total supply risk, $\text{risk} = \mathbf{w}^T \cdot \mathbf{\Pi} \cdot \mathbf{w}$, is normalized:

$$0 \leq \text{risk} \leq 1,$$

where $\mathbf{w}^T := (w_1, ..., w_f, ..., w_F)$ and $w_1 + ... + w_F = 1$. $\mathbf{\Pi}$'s diagonal elements π_{ff} equal the fuel-specific risks, $\pi_{ff} = \text{risk}_f = x_{fd}^2 r_d + \sum_j x_{fj}^2 r_j$, while the off-diagonal elements are given by $\pi_{f_1 f_2} = x_{f_1 d} x_{f_2 d} r_d + \sum_j^J x_{f_1 j} x_{f_2 j} r_j, f_1 \neq f_2$.

Proof of Proposition II: While according to Proposition 1 the fuel-specific risk $\pi_{ff} = \text{risk}_f$ is normalized, it is now first shown that $0 \leq \pi_{f_1 f_2} \leq 1$ for $f_1 \neq f_2$. As a sum of products of exclusively non-negative factors, it is evident that $\pi_{f_1 f_2}$ is non-negative. Furthermore, $\pi_{f_1 f_2}$ does not exceed unity, as $r_d \leq 1$, $r_j \leq 1$, $0 \leq x_{f_1 d}$, $0 \leq x_{f_1 j}$, and $0 \leq x_{f_2 d} \leq 1$ as well as $0 \leq x_{f_2 j} \leq 1$:

$$\pi_{f_1 f_2} = x_{f_1 d} x_{f_2 d} r_d + \sum_{j}^{J} x_{f_1 j} x_{f_2 j} r_j \leq x_{f_1 d} x_{f_2 d} + \sum_{j}^{J} x_{f_1 j} x_{f_2 j} \leq x_{f_1 d} + \sum_{j}^{J} x_{f_1 j} = 1.$$

Second, based on $0 \leq \pi_{f_1 f_2} \leq 1$ for all $f_1, f_2 = 1, ..., F$, it follows from $w_1 + ... + w_F = 1$ that

$$\text{risk} = \mathbf{w}^T \cdot \mathbf{\Pi} \cdot \mathbf{w} = \sum_{f_1=1}^{F} \sum_{f_2=1}^{F} w_{f_1} \cdot \pi_{f_1 f_2} \cdot w_{f_2} \leq \sum_{f_1=1}^{F} \sum_{f_2=1}^{F} w_{f_1} \cdot w_{f_2} = (\sum_{f_1=1}^{F} w_{f_1}) \cdot (\sum_{f_2=1}^{F} w_{f_2}) = 1.$$

Several other properties of risk indicator (1) deserve noting: First, defining the fuel-specific risk on the basis of a quadratic form implies that the risk contribution of an export country j that provides for only a small fraction of, say, x_{fj} = 3 % of the domestic supply is rather negligible. The weight x_{fj}^2 of such a country in expression (1) is as low as 0.0009. Using squared shares as weights seems to be sensible, as in practice export countries with small contributions to the domestic supply should be quite irrelevant for a nation's energy security situation.[9]

Second, given variety, improving the import balance among countries with the same risk characterization should diminish the supply risk. In formal terms, given $\mathbf{x}_f^T := (x_{fd}, x_{f1}, ..., x_{fj}, ..., x_{iJ})$, where without any loss of generality $x_{f(J-1)} > x_{fJ}$ and $r_{J-1} = r_J$, the more balanced distribution given by $\hat{\mathbf{x}}_f^T := (x_{fd}, x_{f1}, ..., x_{f(J-2)}, \hat{x}_{f(J-1)}, \hat{x}_{fJ})$ with $\hat{x}_{f(J-1)} = \hat{x}_{fJ} = (x_{f(J-1)} + x_{fJ})/2$, indeed leads to a lower supply risk:

$$\widehat{\text{risk}}_f := \hat{\mathbf{x}}_f^T \cdot \mathbf{R} \cdot \hat{\mathbf{x}}_f = x_{fd}^2 \cdot r_d + \sum_{j=1}^{J-2} x_{fj}^2 r_j + 2r_J (\frac{x_{f(J-1)} + x_{fJ}}{2})^2 < x_{fd}^2 \cdot r_d + \sum_{j=1}^{J} x_{fj}^2 r_j = \text{risk}_f.$$

This holds because

$$2r_J(\frac{x_{f(J-1)} + x_{fJ}}{2})^2 = \frac{r_J}{2}(x_{f(J-1)}^2 + 2x_{fJ}x_{f(J-1)} + x_{fJ}^2) < \frac{r_J}{2}(2x_{f(J-1)}^2 + 2x_{fJ}^2) = r_J(x_{f(J-1)}^2 + x_{fJ}^2),$$

as $(x_{f(J-1)} - x_{fJ})^2 > 0$ for $x_{f(J-1)} > x_{fJ}$ and, hence, $2x_{fJ}x_{f(J-1)} < x_{f(J-1)}^2 + x_{fJ}^2$.

Third, given a perfectly balanced supply situation $\mathbf{x}_f$ of fuel f characterized by $x_{fd} = x_{f1} = ... = x_{fj} = ... = x_{fJ}$, it is obvious that any risk indicator should monotonically decrease with an increasing variety of imports, provided that the additional imports originate from further export countries that display no risks. Finally, it is intuitive that increasing diversification by splitting up the imports originating from a

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[9] In a similar vein, the so-called penalization functions emerging from the mathematical and statistical literature are frequently of quadratic nature. Besides HERFINDAHL's index and the mean-squared error (GREENE 1993:94), another prominent example of a statistical penalization function is the sum of squared residuals that is minimized with respect to the parameters to be estimated when using the method of Ordinary Least Squares. Using this method implies that larger residuals get a higher penalty than small residuals. This appears to be reasonable, as small residuals may reflect chance, whereas large residuals may be due to systematic deviations.

single country, say country J, would reduce the supply risk if the contribution x_{fJ} is then shared by two countries with the same risk characterization $r_J = r_{J+1}$, so that $x_{fJ} = \tilde{x}_{fJ} + \tilde{x}_{f(J+1)}$.

Appendix C: OECD and World Bank Indicators

Table C1: Normalized OECD and World Bank Risk Indicators.

Country	Risk		Country	Risk	
	OECD	World Bank		OECD	World Bank
Algeria	0.43	0.61	Netherlands	0.00	0.09
Angola	0.86	0.68	Nigeria	0.86	0.72
Canada	0.00	0.09	Norway	0.00	0.07
China	0.29	0.52	Poland	0.29	0.37
Colombia	0.57	0.56	Russia	0.43	0.61
Ecuador	1.00	0.67	Saudi-Arabia	0.29	0.49
Germany	0.00	0.13	South Africa	0.43	0.38
Iran	0.86	0.68	U.S.	0.00	0.18
Iraq	1.00	0.85	United Arab Emirates	0.29	0.29
Kuwait	0.29	0.37	United Kingdom	0.00	0.12
Libya	1.00	0.59	Venezuela	0.86	0.72
Mexico	0.29	0.50	Others	1.00	1.00

Sources: OECD (2008), World Bank (2008). Note: 1 stands for extremely instable countries, whereas 0 indicates stable countries.

Covering 209 countries, the five so-called Aggregate Governance Indicators provided by the World Bank (2008) account for political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. The values of these security indicators lie between -2.3 in the worst case and approximately 1.9 for the best conditions. To allow for comparisons with the OECD classifications, we have normalized each of the five indicators to range between 0 and 1, first by shifting each indicator to the positive realm before dividing the outcomes by the highest values of the individual indicators, respectively. For each indicator, the results have then been subtracted from 1 to get a risk, rather than a security classification. Finally, taking the country-specific means of the modified indicators provides for the figures reported in Table C1.

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