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Abstract

The security of energy supply has again become a similarly hot topic as it was during the oil crises in the 1970s, not least due to the recent historical oil price peaks. In this paper, we analyze the energy security situation of the G7 countries using a statistical risk indicator and empirical energy data for the years 1978 through 2007. We find that Germany's energy supply risk has risen substantially since the oil price crises of the 1970s, whereas France has managed to reduce its risk dramatically, most notably through the deployment of nuclear power plants. As a result of the legally stipulated nuclear phase-out, Germany's supply risk can be expected to rise further and to approach the level of Italy. Due to its resource poverty, Italy has by far the highest energy supply risk among G7 countries.

1 Introduction

Today, we experience the confluence of continuing instability in the Middle East, a growing resource nationalism, Russia's annual gas supply interruptions directly following the New Year's fireworks, and a surge of oil demand by emerging countries, particularly China. This has made energy supply security a high policy priority in the European Union (COM 2008a). Yet, despite the almost ever-increasing significance of this topic, there are just a few contributions to the literature that have developed and employed quantitative (in)security measures, with FRONDEL and SCHMIDT (2008), GRUBB et al. (2006), MARKANDYA et al. (2005), and JANSEN et al. (2004) being among the most recent studies.

In this paper, we empirically analyze both the past and future energy security situation of G7 countries using the statistical indicator of the long-term energy supply risk conceived by FRONDEL and SCHMIDT (2008). This indicator condenses empirical information on the imports of fossil fuels, such as oil, gas, and coal, originating from a multitude of export countries, as well as data on the indigenous contribution to the domestic supply of all kinds of energy sources, including biofuels and other renewable energies. The empirical outcome is a single figure that characterizes the total risk of a country's reliance on fossil fuel imports at a given point in time. While taking account of all energy sources used in a country, both renewable and non-renewable, the basic ingredients of our concept are (1) a country's own contribution to the total domestic supply of any fuel vis-a-vis the fuels' import shares, (2) the probabilities of supply disruptions in export countries, and (3) the diversification of the primary energy mix, that is, the variety of energy sources and technologies employed to satisfy demand.

The following section provides for a short summary of the empirical concept that FRONDEL and SCHMIDT (2009) suggest for measuring a country's long-term energy supply risk. In Section 3, this concept is applied to empirical data of G7 Countries provided by the International Energy Agency (IEA) for the past (1978-2007), as well as to projections for 2020, followed by an in-depth analysis explaining the outcomes of our risk calculations. The last section summarizes and concludes.

2 An Empirical Supply Risk Measure

While there are several competing concepts, FRONDEL and SCHMIDT (2008) build on the work of JANSEN et al. (2004) in that their risk indicator strongly relies on the notion of diversity. Yet, in contrast to JANSEN et al. (2004), who base their energy security indicator on SHANNON's (1948) diversity measure, the risk indicator's fundamental basis is HERFINDAHL's (1950) concentration index. This choice is due to FRONDEL and SCHMIDT's (2008) scepticism concerning whether any meaningful security indicator may be based on SHANNON's diversity measure. In the following section, we will demonstrate for the example of G7 countries that FRONDEL and SCHMIDT's risk indicator is meaningful indeed: The inter-temporal picture drawn on the basis of our risk calculations appears to be perfectly in line with our qualitative analysis of these country's primary energy supply mix.

Denoting the probability of supply disruptions in export country j by r_j, FRONDEL and SCHMIDT (2009) suggest the following quadratic form as a measure capturing a nation's supply risk related to fuel i:

$$\text{risk}_i := \mathbf{x}_i^T \cdot \mathbf{R} \cdot \mathbf{x}_i = x_{id}^2 \cdot r_d + \sum_{j=1}^{J} x_{ij}^2 \cdot r_j, \tag{1}$$

where the share of export country j in the domestic supply of energy resource i is designated by x_{ij}, and the respective indigenous contribution by x_{id}. By definition,

$$x_{id} + x_{i1} + ... + x_{ij} + ... + x_{iJ} = 1, \quad i = 1, ..., I. \tag{2}$$

The risk-characterizing matrix $\mathbf{R}$ is defined by $\mathbf{R} := \mathbf{r}^T \cdot \mathbf{I}$, 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. Arguably, the probability of a disruption of a nation's own contribution to domestic supply can be assumed to equal zero: $r_d = 0$.

From the perspective of an import country, the components of share vector $\mathbf{x}_i$ defined by $\mathbf{x}_i^T := (x_{id}, x_{i1}, ..., x_{ij}, ..., x_{iJ})$ are the primary instruments to improve supply security. If x_{id} equals unity, a nation is autarkic with respect to fuel i. In this polar case, the supply risk related to fuel i, as defined by (1), takes on the minimum value of zero, indicating a perfectly secure fuel supply. In the opposite polar case, in which the total

supply of fuel i exclusively originates from highly instable export countries such that $r_j = 1$ for all countries $j = 1, ..., J$, risk_i takes on the maximum value of unity. In short, the fuel-specific risk defined by (1) is normalized: $0 \le \text{risk}_i \le 1$.

Definition (1) comprises three major aspects of energy security: (1) a country's own contribution x_{id} to the total domestic supply of fuel i, (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 $\mathbf{x}_i$. The role of diversification is incorporated in the fuel-specific indicator risk_i by building on HERFINDAHL's (1950) index, with which one can measure the concentration of fuel imports:

$$H_i := s_{i1}^2 + ... + s_{ij}^2 + ... + s_{iJ}^2, \tag{3}$$

where s_{ij} denotes the share of export country j in total imports of fuel i. The share s_{ij} relates to country j's contribution x_{ij} to the total domestic supply of fuel i as follows:

$$x_{ij} = s_{ij}(1 - x_{id}). \tag{4}$$

According to this expression, increasing the indigenous contribution x_{id} decreases x_{ij}, thereby alleviating the import dependency with respect to fuel i and, hence, risk_i.

To measure a nation's entire vulnerability with respect to all kinds of energy imports, FRONDEL and SCHMIDT (2009) suggest evaluating the following generalization of the fuel-specific supply risk defined by (1):

$$\text{risk} := \mathbf{w}^T \cdot \mathbf{X}^T \cdot \mathbf{R} \cdot \mathbf{X} \cdot \mathbf{w} = \mathbf{w}^T \cdot \mathbf{\Pi} \cdot \mathbf{w}. \tag{5}$$

$\mathbf{w}^T := (w_1, ..., w_i, ..., w_I)$ represents a vector whose non-negative components w_i reflect the shares of the various fuels and energy sources in a nation's total energy consumption and, hence, add to unity: $w_1 + ... + w_I = 1$. 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 I fuels and energy sources:

$$\mathbf{X} := \begin{pmatrix} x_{1d} & . & x_{id} & . & x_{Id} \\ x_{11} & . & x_{i1} & . & x_{I1} \\ . & . & . & . & . \\ x_{1j} & & x_{ij} & & x_{Ij} \\ . & . & . & . & . \\ x_{1J} & . & x_{iJ} & . & x_{IJ} \end{pmatrix}. \tag{6}$$

The diagonal elements π_{ii} of the product matrix $\mathbf{\Pi} := \mathbf{X}^T \cdot \mathbf{R} \cdot \mathbf{X}$ are identical to the fuel-specific supply risks: $\pi_{ii} = \text{risk}_i = \sum_j^J x_{ij}^2 r_j \geq 0$. Non-vanishing off-diagonal elements, $\pi_{kl} = \sum_j^J x_{kj} x_{lj} r_j > 0$ for $k, l = 1, ..., I, k \neq l$, take account of the fact that, for instance, oil supply disruptions in an export country may be correlated with those of gas. Finally, it bears noting that the total supply risk (5) falls between zero and unity. In practice, though, the indicator's concrete outcome is typically much smaller than unity.

3 Energy Supply Risks of G7 Countries

On the basis of energy data provided by the International Energy Agency (IEA), we now employ these concepts to compare the past and future energy supply risks of the G7 countries. 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 have been weighted to lie within the range of zero to unity, are displayed in Table A1 of the appendix. Although these classifications are commonly used to gauge loan loss risks, they should also satisfactorily characterize a country's political and economic situation, as political risks and other risk factors are also integrated into the OECD assessment.

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 almost unaltered. Furthermore, our calculations are based on the assumption that nuclear power, as well as renewable energy sources, should be treated as a domestic resources. The explanation for this treatment is 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 is also the prevailing practice in international energy statistics.

Using the country-specific primary energy mix given in the appendix, as well as the fuel import shares that can be obtained from the IEA statistics, the application of risk indicator (5) reveals that Germany's and Italy's energy supply risks rose substantially over the period from 1978 to 2007, whereas France and Japan have managed to reduce their risks dramatically, thereby reaching an almost similarly relaxed energy security situation as the U. S. and the U. K. (see Figure 1). Together with Canada, whose energy supply risk is close to zero, these are the resource-rich G7 countries.

Figure 1: **G7 Energy Supply Risks (Germany 1980:100)**
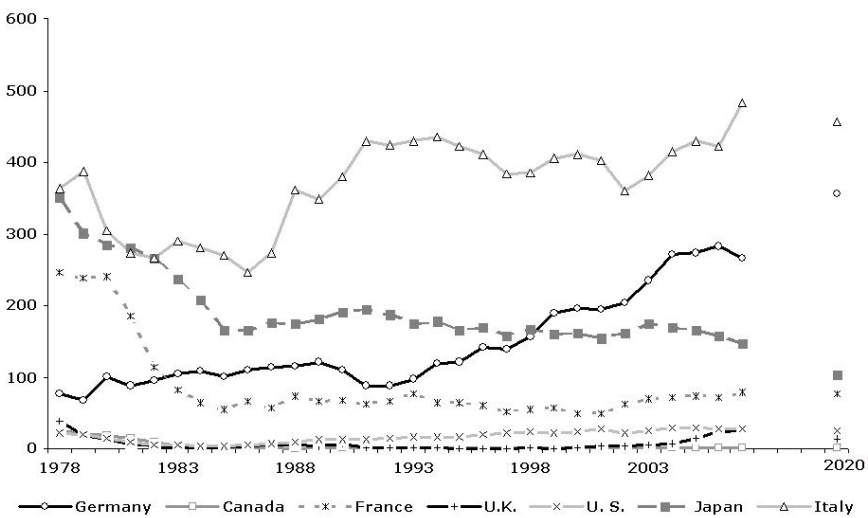
Today, Germany's energy supply risk is only surpassed by that of Italy. In the past, this was not always the case: At the beginning of the 1980s, France and Japan exhibited much larger energy supply risks than Germany. In contrast to Germany, though, France has been able to reduce its risk, above all through the massive deployment of nuclear

power plants. As a consequence, the contribution of nuclear power to the primary energy mix increased from about 8% in 1980 to nearly 43% in 2007, whereas the share of oil decreased from about 56% to 33% between 1980 and 2007 (see Table A2 of the appendix). Among all G7 countries, France displays by far the largest share of nuclear energy, being one major reason for its rather relaxed supply situation today.

Japan reduced its energy supply risk in comparable dimensions as France. Part of the story has been an increase in the share of nuclear power, albeit a rather moderate one, from 6% in 1980 to slightly more than 13% in 2007 (see Table A3). In addition, Japan improved the diversity of supply by increasing the relative contributions of natural gas and hard coal. At the same time, the former dominance of oil was diminished substantially, with the oil share being reduced from about 75% to 46% in 2007. In contrast, brown coal is not used at all due to the lack of any reserves in Japan, while renewable energy technologies play only a minor role. Not least, Japan spread its gas imports among a growing number of energy exporting countries, thereby achieving a significant reduction of its gas-specific risk (see Figure 2).

Figure 2: **Gas-Specific Risks**
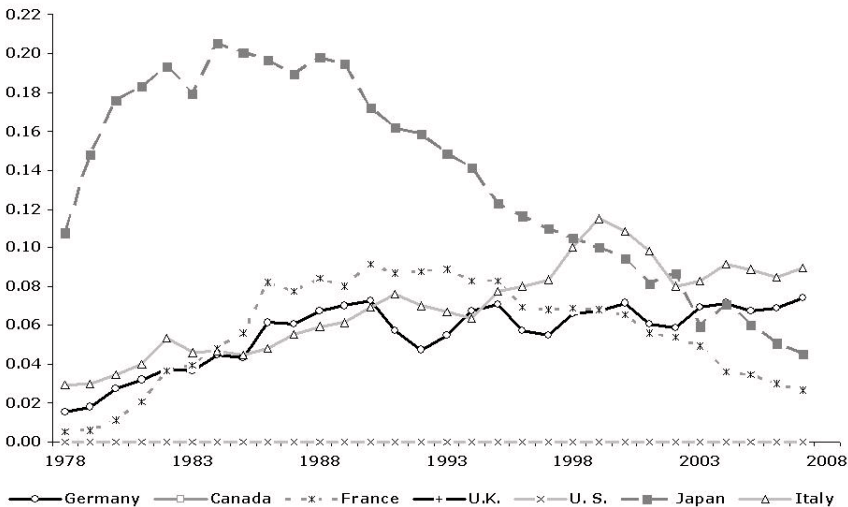
In contrast to Japan, Germany's imports of oil and gas has concentrated more and more on Russia, thereby substituting the former dependence on OPEC oil with a strong

reliance on Russia's oil, gas, and coal reserves. At present, Russia is by far Germany's most important oil provider, being responsible for as much as about 40% of total oil supply. As a consequence, the country's oil supply risk has roughly doubled – in terms of the fuel-specific indicator (1) – between 1980 and 2007 (see Figure 3). Furthermore, the drastic decline of Germany's relative contribution to its domestic gas supply has been encountered by surging gas imports from Russia. The current 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, Russia's abundant energy reserves played only a minor role for Germany in the 1970s. Not surprisingly, therefore, Germany's gas supply risk has more than doubled since then (see Figure 2).

Figure 3: **Oil-Specific Risks**
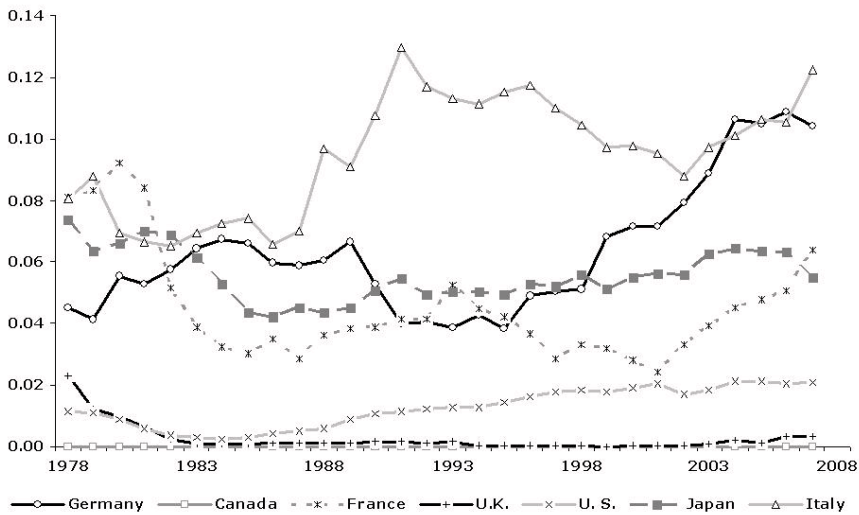
That Germany's energy supply situation has deteriorated substantially since the oil price crises of the 1970s has another reason in the decline of German hard coal, which is due to the widening gap between domestic production cost and world market prices of coal (FRONDEL et al. 2007). Within the next decades, Germany's energy supply risk is likely to rise much further: Given the nuclear phase-out decision, which stipulates the end of nuclear power in Germany at around 2024, and the foreseen dismantling of the hard coal subsidies by 2018, our calculations suggest that Germany's energy supply risk can be expected to rise even if the national goal of a 30% share of electricity production

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from renewable energies will be reached in 2020 (see Figure 1). A major reason is that, based on the present share in electricity production of about 15%, the required increase in "green" electricity is much lower than the contribution of nuclear power, which currently amounts to almost 30%. By contrast, given the projections for 2020 presented in the tables of the appendix, our calculations of the future energy supply risks of all other G7 countries indicate that the risks either stagnate or further decrease, as is to be forecasted for Japan for example.

Similar to Germany, the supply risk of Italy has increased significantly over the last decades. The country displays by far the highest energy supply risk across G7, owing primarily to its highly undiversified energy mix: For Italy, brown coal and nuclear energy do not contribute to the energy supply at all, while oil and gas play an overwhelming role (see Table A5). It is thus all the more critical that Italy depends so heavily on oil and gas imports, with import shares being 93% and 88%, respectively. It is not surprising, therefore, that the oil- and gas-specific risks of Italy are the highest among all G7 countries (see Figures 2 and 3), as well as the fuel-specific risk regarding hard coal (Figure 4). The hard-coal specific risk has increased substantially since 2000 due to the rising share of imports from Indonesia, which increased from some 10% to about 32% in 2007, whereas the hard coal imports from highly reliable countries such as Australia, Canada, and the U. S. shrank. With the highest risks with respect to oil, gas, and hard coal, it is no wonder that Italy faces the highest energy supply risk altogether.

Relative to the risk values of Italy and Germany, there is a large gap between the energy supply risks of both these nations and the resource-rich countries of Canada, U. K. , and the U. S. While Canada's supply risk has remained negligible for decades, the U. S. risk has risen moderately since the oil crises of the 1970s. Mainly, this increase can be attributed to the growing share of oil imports due to the decline in domestic oil production, resulting in an increase of the oil-specific risk (Figure 3). In contrast, the coal- and gas-specific risks appear to be insignificant. Given these low risk judgments, the enormous efforts in producing bio-ethanol, derived mainly from maize and spurred by tax incentives (IEA 2006e:387), seem to be rather irrelevant for energy security reasons. In 2006, the U. S. became the world's largest producer of bio-ethanaol

(IEA 2006e:387), thereby employing large fractions of more than one third of its annual maize production for this task.

Finally, there has been a moderate increase in the total supply risk of the U. K. , most notably because the hard-coal specific risk has grown significantly (Figure 4), whereas the oil- and gas-specific risks have remained zero. Responsible for the increase in the hard-coal specific risk was the declining domestic production. Its share in total supply fell from 57.1% in 2000 to 26.9% in 2007, while the dependence on Russian imports rose from 9.0% to 33.5% in same period of time.

Figure 4: **Hard-Coal-Specific Risks**
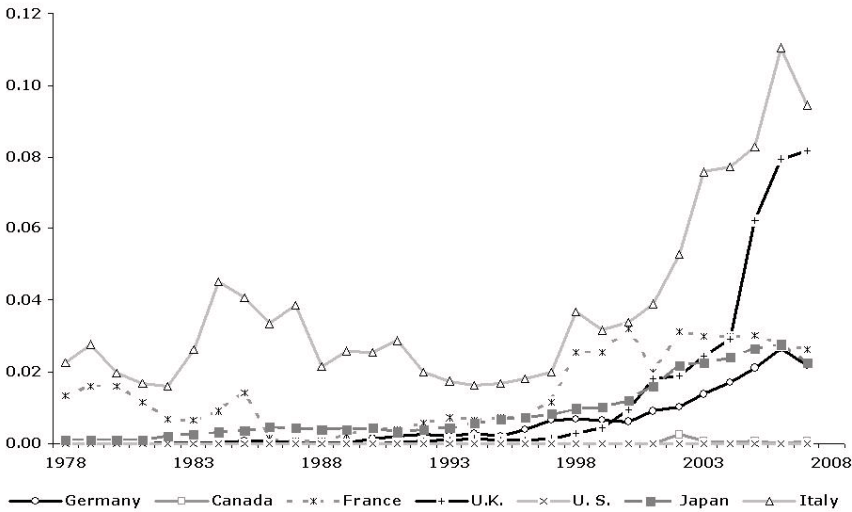
4   Summary and Conclusion

Using FRONDEL and SCHMIDT's (2008) risk indicator, this article suggests that, concerning their energy supply risks, the G7 countries can be classified into three groups. The first group consists of the energy-rich countries Canada, the U. K. and the U. S., whose energy security situation appears to be rather relaxed: The calculated risk values are quite moderate and rather stable. Most important for this result is that, although not entirely self-sufficient, these country's fuel imports are divided among relatively sta-

ble countries. France and Japan, the members of the second group, have managed to reduce their risks by diversifying both their primary energy mixes and supply structures. In France, this was mainly achieved by drastically increasing the contribution of nuclear power, which is treated here, as well as in in international energy statistics, as a domestic resource. Germany and Italy, finally, are the only G7 countries whose energy supply risks rose substantially over the period from 1978 to 2007.

The qualitative analysis of the primary energy mix and the diversification of fuel imports substantiates our risk calculations, thereby reconfirming the picture drawn in Figure (1). A key reason for the increased energy supply risk in Germany is its rising dependence on Russian oil and gas, and most recently, its increased hard coal imports. At present, Russia is by far Germany's most important oil and gas provider, being responsible for as much as about 40% of total oil and gas supply, respectively. With the completion of the new gas pipeline called Nord Stream, it is most likely that Western Europe's reliance on Russian gas will grow much further, not least due to the shrinking gas production of the U. K. and the Netherlands. Given such perspectives, it is not surprising that Italy, which highly depends on gas and oil imports due its abstinence from nuclear energy, reconsiders the deployment of nuclear power plants. With the legally stipulated nuclear phase-out, Germany therefore seems to be isolated not only among G7 countries, but almost all over the world.

Appendix

Table A1: Normalized OECD Risk Indicators

Country	Risk	Country	Risk
Algeria	3/7	Netherlands	0
Angola	6/7	Nigeria	6/7
Canada	0	Norway	0
China	2/7	Poland	2/7
Colombia	4/7	Russia	3/7
Ecuador	1	Saudi-Arabia	2/7
Germany	0	South Africa	3/7
Iran	6/7	U.S.	0
Iraq	1	United Arab Emirates	2/7
Kuwait	2/7	United Kingdom	0
Libya	1	Venezuela	6/7
Mexico	2/7	Others	1

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

Table A2: **Primary Energy Mix of France**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	61.1	55.9	40.6	38.4	35.3	33.9	33.5	32.9	32.1
Gas	10.1	11.2	11.9	11.4	12.3	13.9	14.6	14.3	14.8
Hard Coal	16.1	16.6	12.2	8.5	6.7	5.8	5.2	5.0	4.5
Nuclear Power	4.3	8.2	28.3	36.0	40.8	42.0	42.5	42.7	41.6
Brown Coal	0.4	0.4	0.3	0.4	0.2	0.0	0.0	0.0	0.0
Renewables	8.0	7.7	6.7	5.3	4.7	4.4	4.2	5.1	7.0

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-,
and solar power as well as biomass. Shares for 2020 are based on COM (2008b).

Table A3: **Japan's Primary Energy Mix**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	74.9	68.0	55.8	57.1	53.7	50.4	47.7	46.0	36.3
Gas	4.7	6.2	9.6	9.9	10.6	12.6	13.3	15.9	18.4
Hard Coal	13.9	17.2	19.7	17.4	17.7	17.5	21.9	21.9	21.5
Nuclear Power	4.6	6.2	11.9	11.8	15.2	16.1	13.8	13.2	18.5
Brown Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Renewables	1.9	2.4	3.0	3.8	2.8	3.4	3.3	3.0	5.3

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-, and solar power as well as biomass. Shares for 2020 are based on IEA (2008d).

Table A4: **Germany's Primary Energy Mix**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	45.0	40.8	34.3	35.3	39.6	38.3	35.9	33.9	35.2
Gas	13.3	14.2	13.5	15.4	19.6	20.9	22.6	22.5	25.3
Hard Coal	15.9	17.5	16.2	15.5	14.8	13.4	12.7	14.3	9.2
Nuclear Power	3.2	4.0	10.0	11.2	11.7	12.9	12.5	11.1	4.1
Brown Coal	22.6	21.7	24.0	20.6	11.9	11.3	11.9	11.6	8.6
Renewables etc.	0.0	1.8	2.0	2.0	2.4	3.2	4.4	6.6	17.6

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-, and solar power as well as biomass. Shares for 2020 are based on EWI, Prognos (2007).

Table A5: **Italy's Primary Energy Mix**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	70.6	69.4	61.0	58.5	57.7	51.3	45.9	44.6	40.0
Gas	16.6	16.3	20.0	25.6	27.7	33.7	36.1	37.0	40.2
Hard Coal	6.8	8.4	11.2	9.6	7.6	7.3	9.1	8.9	9.4
Nuclear Power	0.9	0.4	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Brown Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Renewables	5.1	5.5	6.5	6.3	7.7	7.7	8.9	9.5	10.4

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-, and solar power as well as biomass. Shares for 2020 are based on COM (2008b).

Table A6: **U. S. Primary Energy Mix**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	48.5	44.4	43.4	40.0	38.4	38.7	40.7	39.3	39.3
Gas	24.4	26.3	23.1	22.8	24.4	23.8	22.1	22.9	21.0
Hard Coal	14.9	20.0	18.9	22.4	24.3	22.6	22.5	22.4	21.5
Nuclear Power	4.1	3.8	7.0	8.3	7.9	9.0	9.1	9.2	9.4
Brown Coal	0.6	0.8	1.3	1.3	1.3	1.0	1.0	1.0	1.0
Renewables	7.5	3.4	6.3	5.2	3.7	4.9	4.6	5.2	7.8

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-, and solar power as well as biomass. Shares for 2020 are based on IEA (2008d).

Table A7: **U. K. Primary Energy Mix**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	45.4	40.8	38.7	38.9	37.9	36.2	35.6	35.5	39.0
Gas	17.6	20.0	22.9	22.2	29.2	37.8	37.4	36.1	34.5
Hard Coal	32.2	34.2	30.5	29.7	21.0	14.8	16.0	18.8	17.4
Nuclear	4.6	4.8	7.8	8.1	10.4	9.6	9.0	7.2	3.3
Brown Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Renewables	0.2	0.2	0.2	1.0	1.5	1.6	2.0	2.5	5.8

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-, and solar power as well as biomass. Shares for 2020 are based on COM (2008b).

Table A8: **Canada's Energy Mix**

	1978	1980	1985	1990	1995	2000	2004	2007	2020
Oil	48.5	46.1	36.3	36.9	33.6	35.0	36.5	35.9	35.9
Gas	24.4	23.6	25.8	26.2	29.1	29.6	29.0	29.0	29.0
Hard Coal	6.4	7.0	7.3	5.4	4.4	6.5	4.8	4.9	4.9
Nuclear Power	4.7	4.1	8.4	9.3	11.0	7.6	8.6	9.0	9.0
Brown Coal	3.0	3.5	5.7	5.3	6.2	5.5	5.5	5.4	5.4
Renewables	13.3	15.7	16.5	16.9	15.7	15.8	15.6	15.8	15.8

Note: Shares are based on IEA (2006c, 2004d, 2006d, 2008b). Renewables include hydro-, wind-, and solar power as well as biomass. Shares for 2020 are identical by assumption.

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