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Abstract

This report is composed by two sections.

Section 1 *reviews the evidence on the macro-economic costs of energy price fluctuations and their impacts on the EU. The majority of the evidence (modelled or observed) relates to the macro-economic costs – in terms of lost GDP – from oil price increases that last at least six months. When these costs are apportioned to EU electricity consumption, they are negligible, a mid-point result being €0.000004 per kWh within a range of €0.000001 - €0.000008. The absence of empirical evidence, however, has meant that impacts of short term oil price fluctuations and the potential impacts of equivalent price movements in gas or coal are not quantified.*

Section 2 *provides an overview of some of the recent literature on the Value Of Lost Load (VOLL). VOLL as monetary expression for the costs associated with inter- or disruptions of electricity supply, as a result of production, transmission or distribution failures, can be a useful variable that allows for the quantification of one of the dimensions of energy supply security of a country, region or economic sector. Through our literature review and a closer inspection of a selection of the most quoted references, we find that figures for VOLL are almost certainly laying in a range of 4-40 $/kWh for developed countries and 1-10 $/kWh for developing countries. With still a high level of confidence these ranges can be narrowed down to, respectively, 5-25 $/kWh and 2-5 $/kWh. We also carefully conclude that these ranges seem left-skewed.*

Section 1 - National and EU level estimates of energy supply externalities

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1. Introduction

This report is the result of the study carried on by the project CASES – Cost Assessment for a Sustainable Energy Systems, in the Work Package 5, which focuses on Security and Reliability of Supply. The first objective of CASES WP5 is: *To derive estimates of externalities related to energy supply insecurities for EU and other selected countries.*

This report presents our preliminary findings related to this objective. It builds upon the methodology we utilised in the EC ExternE – Pol research project that reported in 2004, (Hunt and Markandya, 2004), and up-dates the estimates derived on the basis of new empirical evidence.

We define energy security as "a state in which consumers and their governments believe, and have reason to believe, that there are adequate reserves and production and supply distribution facilities available to meet their requirements in the foreseeable futures, from sources at home and abroad, at costs which do not put them at a competitive disadvantage or otherwise threaten their well-being. Insecurity arises as a result of physical failure of supplies or as a result of sudden and major price changes", (Belgrave, 1987 cited in Lockwood, 1997). This accords with the International Energy Agency definition as being the "availability of regular supply of energy at a reasonable price" (IEA: 2001).

The ExternE-Pol research was undertaken in the wake of the European Union's Green Paper on energy of 2000. Since then, another Green Paper on energy has been published in 2006, entitled 'A European strategy for sustainable, competitive and secure energy' (EU 2006). This makes reference to energy security issues, and makes explicit the linkages with climate change policy and competitiveness. In addition, EU enlargement, and the string of high-profile energy blackouts in the USA/Canada and Europe in 2003 have served to keep energy security high on the political agenda. The research topic therefore remains germane to evolving energy policy in the EU.

For European policy makers, energy security is an important issue because private decisions about energy use may not fully take into account the costs of energy insecurity. Disruptions in supply and dramatic price increases have macroeconomic impacts that individuals/firms do not take into account. Furthermore, agents tend to underestimate the risks of disruption and subsequent price adjustments, and there are other less tangible effects such as the psychological costs of people feeling insecure about their energy supplies. Therefore, it is important from a policy perspective, to estimate the size of the external costs of energy arising from energy insecurity.

As noted in Hunt and Markandya (2004), three potential kinds of externality associated with energy security exist: These are:

- **Monopsony wedge externality** e.g. when the additional demand for imported oil from a country e.g. Germany, results in the world price of oil rising and so exerts an additional cost on other oil importing countries. Germany will – from an economically rational standpoint – ignore the additional cost to other countries and so constitute an external cost. Note that there is no market failure in terms of global inefficiency, but resulting financial transfers out of a country/EU may be of concern. In practice, this effect seems likely to occur in the case when a purchasing country or group of countries with sufficient market power to influence the market price increases (reduces) their demand. Thus, a shift in demand in the EU may, for example, impose an external cost on the US, or vice versa.

- **Incomplete rent capture** The consumer surplus – here understood as economic rent – is the difference between the market price and the price the consumer would be willing to pay for a given fuel mix quantity. It exists because of the inability of the supplier to capture the full rent from consumers using differentiated pricing strategies. Thus, an energy mix change within a country, e.g. as a consequence of a greater proportion of imported gas, will lead to a change in the level of this rent and so result in an externality.

- **Macroeconomic Externalities**. These result from changes in the international energy markets, e.g. increases in the price of oil, that impact on an importing or exporting country differentially, and in markets other than the energy market.

This research found major limitations in techniques available for measuring in quantitative terms the first two types of externalities described above. Consequently, we focus our efforts on exploring the third type – the macroeconomic externalities.

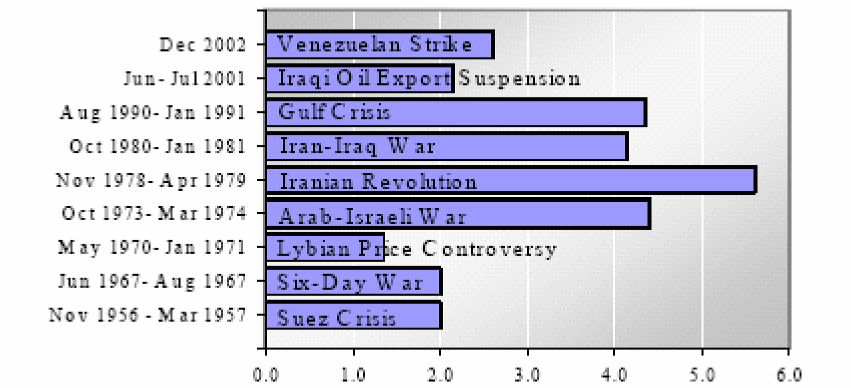
Macroeconomic externalities are examples of pecuniary externalities where the actions of one economic agent affects another through changes in price(s). This means the measurement of any externalities has to be done through economic means, either modelling the economy or through empirical estimation. Modelling allows specific changes to be assessed, but requires an accurately developed and calibrated model – this can be expensive and the information required can be hard to obtain. Empirical estimation, by contrast, benefits from being derived directly from real-world data but suffers from having to find a specific outcome (i.e. size of the externalities) from a general dataset (i.e. the economic data). In the subsequent analysis, we use evidence from both methods – modelled and empirical - and estimate the gross cost of fuel price uncertainty to find the upper bound of the energy security externalities. It represents an upper bound only because it is unrealistic to imagine that all the macroeconomic costs of energy price uncertainty are as a result of impacts in non-energy markets and so constitute external costs Without a means of apportioning the macro-economic costs, however, the total macro-cost estimates are used.

2. *Macroeconomic costs of energy insecurity*

Below, we report on a literature review of the impacts of energy insecurity relating to oil, gas and coal as it relates to electricity supply, with the focus on the EU region. On the basis of the findings of this review we make first estimates of the 'externality unit values' for energy insecurities. The majority of empirical work has been in relation to oil, and our work reflects this, focusing primarily on macroeconomic costs of oil market uncertainties, though also briefly discussing evidence relating to coal and gas.

Since the 1950s, there have been a number of oil shocks – a shock being defined as an unexpected event that has a prominent position in the causality chain of the economy – being either *random shocks* e.g. terrorism; or *strategic shocks* e.g. OPEC manipulating the quantity and therefore price of crude oil. Figure 1 illustrates a number of macro-economically significant supply shortfalls since the Suez crisis in 1957 until 2002 (see also Figure 2 for oil prices from 1998-2006).

Figure 1: Magnitude of oil supply shortfall (mb/d) 1957 to 2002



Source: Harks 2003, in Costantini & Gracceva, 2004:2

The mechanisms through which pecuniary externalities arise are described in the paragraphs below. However, the classification of all macroeconomic costs as externalities is not universally accepted and the identification of an externality effect is important in determining appropriate policy responses.

Macro-economic mechanisms associated with energy market change

Macro-economic consequences of energy market changes have to date largely been the consequences of activities in the world oil market though, in principle, were there to be similar dependence on other imported fuels in the energy mix the mechanisms would apply to these other fuel sources. Thus, whilst the following section identifies empirically observed mechanisms by which oil price increases bring about macroeconomic changes, these may be seen to be based on generic macro-economic principles.

Oil price increases and the macro-economy linkages

Following the majority of economic modelling of energy prices and their macro-economic linkages - there is a clear line of causation from oil price increase to macro-economic impact that exists:

1) Payment for oil imports results in a worsening trade balance for an importing country, (since higher fuel prices result in an increase in total payments - assuming fuel price inelasticity);

2) The consequent current account and balance of payments deficits, and associated depreciation of the exchange rate, results in other more costly imports from outside the EU.

3) Higher import costs – of oil and other commodities - may lead to higher price levels and inflation; higher unemployment may result from the transfer of resources needed to pay for the oil imports; lower GDP may result.

This is a simplification of the central mechanism. There is considerable discussion, (e.g. in Bohi and Toman (1996)), about a number of complicating factors in the operation of such a mechanism. For example, the terms of trade effects may be positive or negative. If a country is reliant and inflexible with regard to its use of oil there will be a greater decline in home output relative to other countries. Therefore whilst the shortage of home-produced goods in world markets will lead to a relative shortage and therefore improved terms of trade, the economy will still worsen. Bohi and Toman (1996) also argue that the relationship between a country's exchange rate and price of oil is ambiguous. After an initial current account deficit from an oil price rise, the effect on the exchange rate in oil importing countries depends on the willingness of oil exporting countries to hold different foreign currencies. If they prefer to hold more dollars (or euros) than other currencies, the dollar will rise at the expense of other currencies. It should be noted that the initial current account deficit may also be mitigated by exchange rate adjustment limiting the upward pressure on import prices, the exchange rate itself likely to be further influenced by other determinants e.g. comparative return rates.

Additionally, whilst it is acknowledged that higher oil prices raise prices, unless these prices continue to rise there will not be on-going inflation. Thus, whilst energy price increases may aggravate existing inflationary processes, they should not necessarily be seen to be the cause of continuing inflation.

Energy security externalities: Identification problems

With these caveats in mind, the following sections provide a review of theoretical and empirical investigations into the macroeconomic effects of oil price shocks. These investigations do not distinguish between internalized and externalized costs, i.e. costs that are not internalized, although there are reasons to think that this distinction is important. For example, Bohi and Toman (1993) make the following argument. They state that in the long run, in response to an energy price change, adjustments take place in the amount of energy-related investment and rate of innovation. Thus, the long run effects on productivity in the energy sector are internalized, (though productivity changes in other sectors are, by definition, not internalized). In the short run, they argue that the macroeconomic effects arise from slow adjustment in the factor and product markets.

First, real wages may not adjust to maintain employment when energy prices rise. A rise in energy prices reduces demand for energy and when energy and labour are complementary, and this will lower the marginal product of labour. Lower productivity implies an increase in the unit cost of labour and employers will seek to reduce the level of employment in response if the wage rate does not adjust to reduce the unit cost. A reduction of employment will lead then to a reduction of overall output. In a similar way to the labour market, the reduction in capital services that results from increased energy prices makes some energy inefficient capital goods superfluous, either from competition, or if the demand for more expensive energy-intensive end products declines. Again, there is a reduction in productive capability and therefore output. These two influences – on the labour and capital markets - may be exacerbated if it is also difficult to reallocate production factors in response to changes in the mix of final demand brought about by changes in product prices.

This analysis raises the question: are these effects on employment and output externalities? The initial price increase is simply representative of a change in resource cost resulting from the need to pay for imports demanded, and the re-alignment of domestic resources. So in this case it seems that costs are fully internalized in private decisions. It is clear, also, that output loss and unemployment may be interpreted either as resulting from imperfections in factor market adjustments or that these factor markets may be operating as well as possible given real world institutional constraints e.g. pay negotiation procedures, competition policy etc. Whichever interpretation we choose, externalities exist to the extent that parties to labour and capital transactions cannot fully avail themselves of the means to anticipate and respond to energy price shocks, whilst if they are anticipated and coped with, effects of energy price variability would be internalized.

There also appears to be the threat of government – rather than market – failure that contributes to the macroeconomic impacts of energy price increases (Bohi and Toman, 1996). For example, because of regulation, an increase in oil prices will not lead to efficient adjustments in gas and electricity prices. These price rigidities may cause adjustment problems throughout economy where regulation cannot simultaneously constrain market power and allow regulated prices to adjust to market conditions.

The preceding paragraphs have made the case that energy security externalities arising from macroeconomic consequences of energy price changes result to the extent that there are factor and product market failures. We make estimates of these externalities in the following sections and highlight some issues relating to the policy implications in the concluding section. The externality estimates are based on the total macroeconomic costs associated with given changes in energy markets. The estimates are derived directly from a review of the historically observed macroeconomic effects of these changes, as well as changes that are simulated in macroeconomic models. In the following analysis we look principally at the impact of sudden, but sustained, increases in price on the macro-economy.

Macro-economic Impacts of Oil Price increases

As Figure 2 shows, there has been a large upwards trend in recent oil prices, driven by a number of factors including increased demand from the Far East – principally China – combined with global production process capacity constraints. In addition to the price rise, the supply capacity constraints also add to the volatility of the market, since the market has less capacity with which to absorb any market shocks. Figure 3 shows that the US government's Energy Information Administration (EIA) of the Department of Energy predicted that the price of oil should fall from a peak in 2007 but there will be long-term rises up to 2030.

A number of general-equilibrium macro-economic models have been developed to simulate the impact of energy price increases and/or supply disruptions on the macro-economy and these have largely focused on the impacts of oil supply shocks that last for a year or more. Note that whilst price volatility in itself has potential macro-economic consequences they are not regarded as being as significant as the sustained price rises resulting from medium term oil price shocks and are not studied separately here.

The outputs of such models are helpful in isolating these impacts from other macro-economic trends – something that a reliance on untreated observational data is unable to do. This section therefore briefly reviews the outputs of a number of these models in terms of their EU-wide macroeconomic costs of energy price rises. In the Externe-Pol research report, Hunt and Markandya (2004) review the published results produced by these models up to 2004 and these are reproduced in
Table 1. Results published subsequently to 2004 are reported in the text below and

Table 2. In general, the differences between the two sets of results are small; we therefore conclude that the same input values used to produce the Hunt and Markandya (2004) external cost estimates are valid to apply in our up-dated calculations, below.

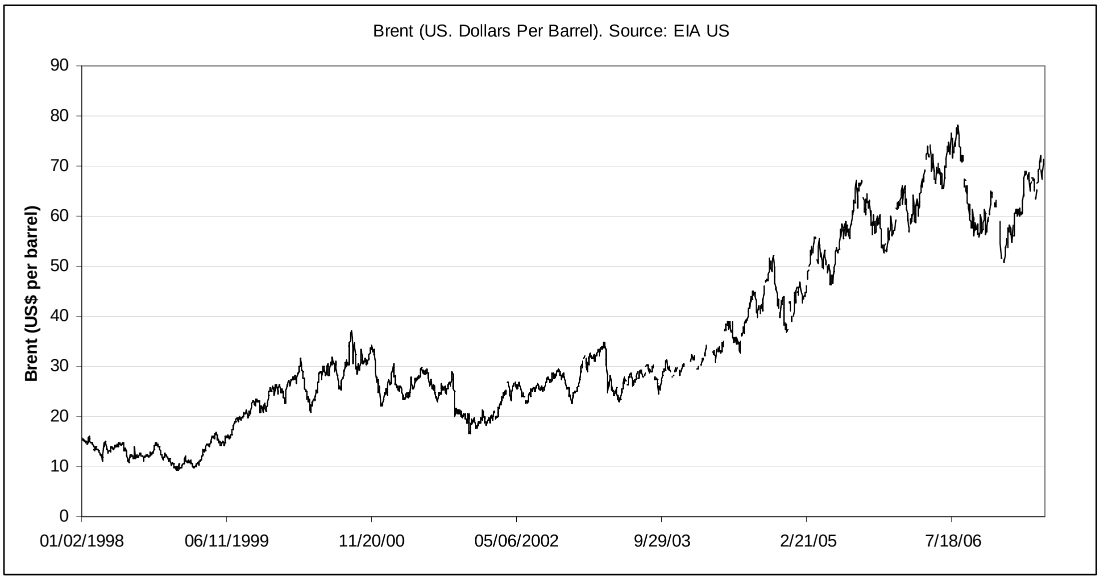


Figure 2: World Prices of Brent Oil 1998-2006 (US$ per barrel). Source: EIA of the USA (http://www.eia.doe.gov/emeu/international/crude1.html)

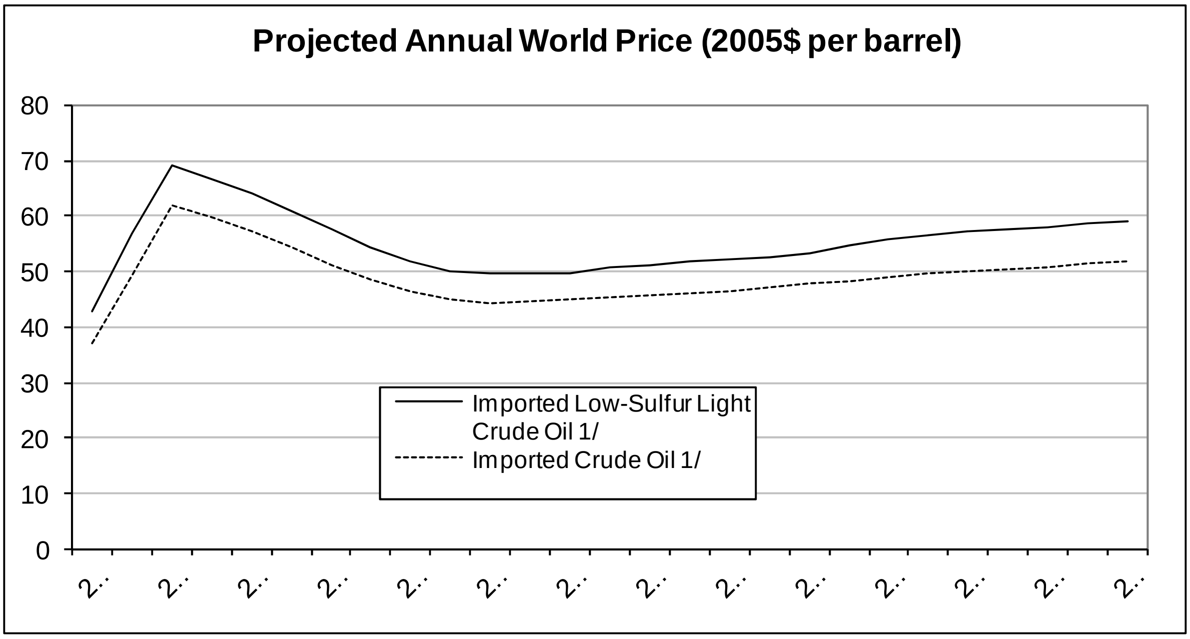


Figure 3: Projected Annual World Price 2004-2030. Source EIA (http://www.eia.doe.gov/oiaf/aeo/pdf/aeotab_12.pdf)

Results from Predictive models

Roeger (2005) used the DSGE model to estimate the effects of a 50% oil price rise on the euro area macro-economy. The paper does not give the baseline price. After 4 quarters, GDP is 0.5% lower than the baseline case, and falls further to 0.6% after 2 years and 0.9% after 5 years. Other studies that have presented results of this kind include World Bank (2005b)

Table 1: Macroeconomic cost estimates of Oil Price increases presented in Hunt & Markandya (2004)

Source	Driver	Estimate	Units	Country / Region
EC (2002)	Sustained $10 increase in price of crude oil (per barrel)	- 0.5%	GDP growth rate	Industrialised countries
IEA (2004)	Sustained increase from $25 to $35 i.e. by $10 per barrel of crude oil	- 0.5%	GDP growth rate	Euro Zone
		0.5%	Inflation	Euro Zone
IMF (2000)	Sustained increase of $5 per barrel of crude oil (20% increase)	- 0.25% (over first four years, then fades to negligible)	GDP growth rate	World
		- 0.4% (percentage deviation from baseline after one year)	GDP growth rate	Euro Area
		0.5% (percentage deviation from baseline after one year)	Inflation	Euro Area
		- 7.8 ($ billion)	Trade balance	Euro Area
IMF (2004)	Sustained increase of $5 per barrel of crude oil (20% increase)	- 0.4% (after one year)	GDP growth rate	Euro Zone
Jones et al (2002)	Price change exceeding a three year high	- 0.05 to – 0.06	Elasticity GDP to oil price shocks	USA
Sauter and Awerbuch (2003)	Sustained 10% rise in oil price	- 1.5% (for 3-6 months)	GDP growth rate	Euro Zone
		- EURO 35 to 70 billion	GDP	Euro Zone
World Bank (2000) in IMF (2000)	50% increase in price in first year, then decline back to original level by the third year.	- 0.25% (over first two years)	GDP growth rate	Industrial countries
		0.2%	Inflation	Industrial countries
Huntington (2004)	Doubling of oil price	-3.7%	GDP	USA and Euro Zone
IEA (2001)	Price level: 1% increase	0.44%	% change in Investment	IEA member countries
	Price volatility: 1% increase	- 0.11%	% change in Investment	IEA member countries

Table 2 Price and output effects from models reported in Roeger (2005) for a 50% increase in oil prices

Model	Price level*			GDP*		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
AWM (1)	0.5	0.9	1.0	-0.1	-0.3	-0.4
QUEST (2)	0.3	0.5	0.6	-0.5	-0.6	-0.7
NIGEM (3)	0.3	0.5	0.9	-0.8	-0.8	-0.7
Interlink (4)	0.6	0.8	0.9	-0.4	-0.2	-0.1
Multimod (5)	1.7	2.7	3.2	-0.1	-0.4	-0.3

* % deviation from baseline; (1) Dieppe et. al. (2004); (2) EU Commission (2004); (3) Barrell et. al. (2004); (4) Dalsgaard et. al. (2001); (5) Hunt et. al (2001)

The summary results presented in
Table 1 and

Table 2, of course, do not reflect the complexity of the models and the variety of their outputs for world regions. Nevertheless, despite the model differences there is some consistency in the pattern and extent of GDP changes. The models show that even when the oil price increase is assumed to be permanent, GDP impacts are likely to be greatest in the first four years of the price increase, and decline subsequently, suggesting that economic agents adapt their expectations to the new price level so that factor and product markets move to new equilibria over this time period. Surprisingly, there is also a degree of consistency in the scale of annual GDP losses associated with specific oil price increases. Thus for the industrialised countries a $10 price increase per barrel gives rise to a 0.5% loss of GDP (EC, 2002) or a proportionate linear scaling of that, on average (IMF, 2000). For the Euro zone countries, there is a similar consistency in the results though here it appears that GDP is more sensitive to oil price increases than for the industrialised countries as a whole. For Euro zone countries, as presented in Table 3, a 50% increase in oil prices results in a 0.4% decline in annual GDP for the first year, simply taking the arithmetic mean of these results, with a range of 0.1% to 0.8%.

Table 3. Impacts on Eurozone GDP of 50% increase in oil prices

Source	Year	Driver	Estimate (%)	Units	Country / Region
Barell and Pomerantz (2004)	2004	**50% increase in oil prices**	-0.8	Devn. from baseline GDP after 1 year	Eurozone
EU Commission (2004)	2004	**50% increase in oil prices**	-0.5	Devn. from baseline GDP after 1 year	Eurozone
Andre et al 2001	2001	**50% increase in oil prices**	-0.4	Devn. from baseline GDP after 1 year	Eurozone
World Bank (2000)	2000	**50% increase in oil prices**	-0.3	Devn. from baseline GDP after 1 year	World
Hunt et al 2001	2001	**50% increase of oil prices**	-0.1	Devn. from baseline GDP after 1 year	Eurozone
Dieppe and Henry (2004)	2004	**50% increase of oil prices**	-0.1	Devn. from baseline GDP after 1 year	Eurozone

There are a number of factors that lead to a high variance in the economic costs of oil price increases, and so potential differences intra-regionally. These differences are summarised in Costantini & Gracceva, (2004) and include:

- The role of fiscal and monetary policy responses. (IEA, (2001)), for example, argues that inappropriate policy responses to oil shocks have led to recessions, where, for instance, highly contractionary monetary policies and fiscal policies to contain inflation reduce national income and increase unemployment.
- Level and duration of the oil price increase - effects are greater the more sudden and pronounced the increase in price;
- Response of oil market. Whether – in the face of a price shock from one source – other suppliers can and do act to alleviate the impact;
- Amount of oil reserves available at the national level
- Import dependence

- Features of the individual national economy, including the weight of energy costs in GDP, the share of energy intensive sector in industry and the prevailing macro-economic state;
- Flexibility of energy sector i.e. capacity to shift from one fuel to another

These factors were also found to be important by Cuñado and de Gracia (2000) when analyzing the differential effects of oil prices on each of the countries within the European Union. They analysed the relationship between oil prices and economic activity for most of the European countries using quarterly data for the period 1960 to 1999. Results are reported in Table 4. They found that the relationship between price and economic activity was only limited to the short-run, with no co-integrating relationship in the long-run. Short-run effects, however, are significant and widely differing between countries and between oil price shocks. The double-digit cuts in production as a result of the 1973-74 price shock were not replicated in subsequent shocks, suggesting some adaptation in market mechanisms. The range of results across countries, though, is diverse and the 1990 oil price shock results in both positive and negative effects. Thus, whilst in our subsequent analysis we use the EU-aggregate results from Table 3, these results should be understood to mask a range of country-specific variance.

Table 4. Country specific impacts in EU of three recent oil price shocks (%)

	1973-1974		1978-1979		1990	
	ΔIPI	Δπ	ΔIPI	Δπ	ΔIPI	Δπ
Germany	-10.22	**0.85**	-4.85	2.85	-2.23	-0.20
Belgium	-13.12	8.07	-9.50	2.35	-3.85	0.31
Austria	-9,45	2.92	-2.14	3.12	0.02	0.84
Spain	-7.54	5.87	-2.16	**0.22**	-2.41	-0.34
Finland	-7.07	7.72	2.81	3.73	-10.40	-0.69
France	-10.99	6.22	-2.94	3.20	-0.43	0.13
Ireland	-6.48	8.75	-5.36	7.20	1.11	0.58
Italy	-14.5	11.36	-2.81	6.57	-3.50	0.46
Luxembourg	**-36.05**	4.99	-12.75	2.52	-2.59	0.34
Portugal	--	**16.85**	--	2.98	-2.59	1.94
United Kingdom	-10.74	6.84	-9.92	**9.45**	**-5.01**	2.21
Netherlands	-11.78	2.69	-2.99	2.25	0.27	1.47
Denmark	-16.29	5.92	-6.92	5.84	-1.32	0.21
Greece	-2.31	**21.55**	-4.57	**10.01**	-3.91	**7.15**
Sweden	-4.41	3.76	-3.90	6.73	-6.71	**4.46**

Note: IPI = Industrial production index (economic activity); Δπ = Inflation growth rate
Source: Cuñado and de Gracia (2000)

3. Estimation of Externality Unit Value

In order to estimate the external effects of energy insecurity in terms of cost per kilowatt hour, we follow the same methodology as in Hunt and Markandya (2004). As with the earlier work, we assume that the main externality is the macroeconomic effects and – indeed – that the macroeconomic effects can be classified as externalities. The schematic presented in Figure 4 shows how the external cost is derived.

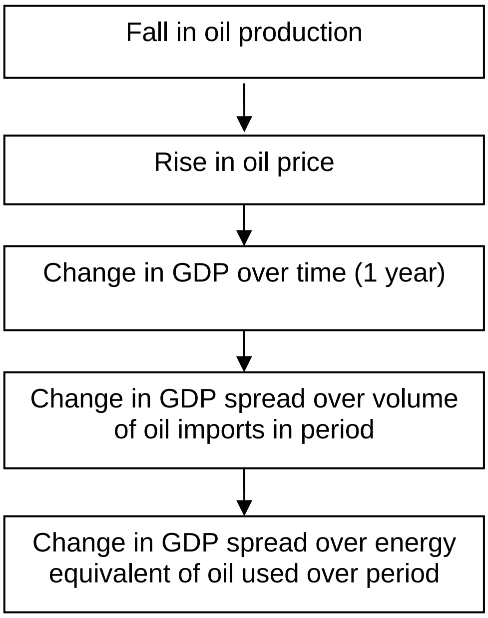


Figure 4. Schematic for estimating macroeconomic variables

A number of strong assumptions are adopted in order to derive these values and these are explained in detail below. In addition, the macroeconomic cost estimates only allow us to include the effect of a sustained price increase. No separate estimates based on price volatility are made since there are - as yet - no good studies of sectoral or macro-economic costs resulting from price volatility (Sauter and Awerbuch (2003)). We therefore assume that the unit value estimates derived below are minima. We assume for simplicity that the time period considered is only one year. The greater uncertainty for impacts in subsequent periods suggests that in the limit this gives rise to a plausible minimum estimate. An upper end estimate could be defined by considering a four year period and multiplying the one-year estimate by 4.

We make the conversion from gross macro-economic costs to costs per kilowatt hour by making a series of steps. The first step is to identify a benchmark for the world oil price against which deviations in price – and therefore GDP - can be measured. as a reference value in the event of an oil price change for instance. However, the predictive models reviewed do not make this assumption explicit. We are therefore obliged to simply adopt the outputs from these models in our analysis. Similarly, whilst we would like to make explicit a second step to apportion a price increase that can be seen as typical to a given oil supply reduction – and thus to allow us to relate a GDP change resulting from a price change to the energy production from a given volume of oil – we have to assume that a 50% price increase (most frequently used in the models) is appropriate. Total GDP for the EU27 in 2005 equated to €10.9 trillion. Therefore, a 0.4% fall in GDP – identified from Table 3 - equates to €43.8 billion p.a. or €175.2 billion over a four year period. For the world as a whole the equivalent figures are €142.7 billion p.a. and €570 billion over the four year period.

In order to express the estimated welfare cost of the oil price change in the same terms as the rest of the CASES externalities, it must be decided whether the loss is expressed per barrel of oil consumed or per barrel of oil foregone. ExternE-Pol's model assumed the latter, as this was the 'opportunity cost' of the price rise. This methodology suggests that these costs are the marginal costs of the price rise. However, we consider that it is more correct to assign the cost across the barrels consumed as this can be taken to be the cost per kilowatt hour of electricity generated. This will give the average cost.

Given that we have now derived a macroeconomic cost per barrel of oil not supplied to the market, i.e. its opportunity cost, we need to make the final conversion to the energy provided by one barrel of oil Three differences between this model and the ExternE-Pol model come to the forefront. A first difference between this model and the ExternE-Pol model is the conversion factor from million barrels per day into kilowatt hours, in particular the calculation of kilowatt hours (kWh) per British Thermal Units (BTU) and also the thermal efficiency factor used in calculating the percentage of possible energy that will actually be converted to electricity. Also, where ExternE-Pol used a conversion factor of 50% to estimate total electricity production per possible kWh output, based on internal discussions this will be reduced to 40% in order to more accurately reflect the energy generating capabilities of oil-fired power plants in the EU[1]. Thirdly, we need to find the correct proportion of oil which is used in generating electricity, as CASES is concerned with the external effects of electricity generation, only. Thus, we estimate the proportion of oil which is used for electricity generation and the proportion of electricity generation which arises from oil-fired power plants. At this stage, aggregated figures for the whole EU will suffice, but disaggregated data could highlight interesting facets of the scenario.

In 2005, Eurostat reports that the EU27 consumed 734 million tonnes of crude oil and feedstocks[2]. As shown in Table 5, In 2004 4% of EU25 electricity production came from oil. Table 6 shows how this proportion varies across countries. The Mediterranean islands have the highest proportion (Malta with 100% and Cyprus with 89%), and the Czech Republic, Luxembourg and Estonia have negligible oil contribution to electricity. This suggests that oil price insecurities when viewed across the EU as a whole may have very small external effects in the electricity generation sector, but for particular countries, the effects may be much more prominent.

Table 5:Sources of Electricity Production in EU25, 2004 (source: IEA)

	Electricity (GWh)	% Total Generation
Production from:		
-coal	974,578	31%
-oil	**130,956**	**4%**
-gas	604,578	19%
-biomass	50,370	2%
-waste	39,223	1%
-nuclear	986,074	31%
-hydro	336,677	11%
- geothermal	5,523	0.17%

[1] http://www.e8.org/index.jsp?numPage=138
[2] Energy monthly statistics – issue number 2/2007

- solar PV	716	0.02%
- solar thermal	510	0.02%
- other sources	60,950	2%
Total Production	**3,190,155**	**100%**

Table 6: Electricity Production from Oil in the EU, 2004 (source: IEA)

	Total Electricity Production (GWh)	Electricity from Oil (GWh)	%
Austria	3190155	130956	4%
Belgium	85643	1676	2%
Bulgaria*	41621	822	2%
Cyprus	4686	4176	89%
Czech	84333	348	0%
Denmark	40477	1633	4%
Estonia	10304	36	0%
Finland	85817	613	1%
France	572241	5855	1%
Germany	616785	10140	2%
Greece	59344	8385	14%
Hungary	33708	773	2%
Ireland	25569	3211	13%
Italy	303347	47140	16%
Latvia	4683	60	1%
Lithuania	19274	361	2%
Luxembourg	4136	0	0%
Malta	2216	2216	100%
Netherlands	100770	2823	3%
Poland	154159	2507	2%
Portugal	45105	5698	13%
Romania*	56499	2199	4%
Slovakia	30567	737	2%
Slovenia	15279	358	2%
Spain	280007	23839	9%
Sweden	151727	1954	1%
UK	395853	4915	1%
Total	**6414305**	**263431**	**4%**

*note: not in EU at time of data

Table 7: **Proportion of Total EU consumption of Oil used for electricity generation (2004)**

Crude oil and petroleum products:	*1000t* Thousands of tons
Input to conventional thermal power stations *(101001)*	28,583
Input to patent fuel and briquetting plants (101003)	18
Input to coke-oven plants (101004)	564
Input to gas-works (101007)	91
Total input to electricity generation	**29,256**
as % gross inland consumption	5%

Source: Eurostat

Table 7 uses data from Eurostat for 2004 to show what quantities of oil and petroleum products are used in electricity generation in the EU25. Inputs to heat-generating plants are not considered but CHP plants are included in table 8. Gross Inland Consumption represents "the quantity of energy necessary to satisfy inland consumption of the geographical entity under consideration." (Eurostat Coded Database). For 2004, Gross inland consumption of oil and petroleum products was 648,865 thousand tonnes, which means that the proportion of oil used in the EU for total electricity generation was 5%. Thus, the percentage of oil price variation that can be apportioned to electricity generation is 4% * 5% = 0.002%.

Since we want an annual equivalent these figures need to be multiplied by the probability of the event occurring in any given year to give us expected values. As an indication the current probability of a price increase of this magnitude occurring can be approximated on the basis of historical data. Harks (2003) estimates that a 3 million barrel shortfall event may be expected to occur at present on a 1 in 5 year frequency, based on historical events. Adopting this probability, the resulting expected value for the EU27 – assuming a 0.4% annual loss in GDP - is €0.000004 per kWh within a range of €0.000001 - €0.000008 for a 0.1% and 0.8% annual GDP loss.

Table 8: Summary of Cost Estimation Process: Oil security externality

	EU27
GDP loss over 1 year (€)	43,798,143,600
GDP loss over 4 years	175,192,574,400
Original oil consumption (mb/day)	82.5
Fall in oil consumption (mb/day)	3
New oil consumption (mb/day)	79.5
Change in GDP per barrel consumed (1 year loss) (€)	1.5
Change in GDP per barrel consumed (4 year loss) (€)	6.0
Each Barrel is equal to 1648.8 kWhs	
Thermal Efficiency	40%
Likelihood of shock	0.2
Cost estimate per kWh - 1year loss (€)	0.002289
Cost estimate per kWh - 4 year loss (€)	0.009154
cost (€/kWh) 1 year loss	0.000458
Cost (€/kWh) 4 year loss	0.001831
Cost proportional to electricity generation (€/kWh)	0.000004

Developing the Model

The model presented above is a simplified model of the economy that asks 'what is the cost of this event happening, and what is the likelihood of the event?' It estimates an upper bound to the external pecuniary effects of a fall in supply of oil to the EU's electricity generating sector.

It is planned that the model will be developed in a number of ways:

- **A dynamic model** would look at the effect of the oil supply shock over time. Complex modelling could be used to estimate how the economy would adjust (price changes versus structural changes, interest rates etc).
- **Precautionary expenditure** Governments and private companies have invested in methods to reduce the effects of oil supply/price variability, such as stockpiling and using the futures market. At the moments these are exogenous to our model, and simply included in the figure of how much the economy reacts to a particular fall, but models could be developed to capture the effect of these policies.
- **Multi-sectoral model** It can be expected that a fall in the price of oil may lead to a fall in the price of substitute goods such as coal or gas in order to maintain productivity. In the case of the electricity generating sector, this may not be worth modelling as the substitutability is governed by electricity generating capacity

Military expenditure

Some have argued that military expenditure should be factored into the external cost of energy security given that without this type of expenditure (particularly in the Middle East) there would be a tangible threat to the secure supply of oil. Delucchi and Murphy (1996) go as far as arguing that if US motor vehicles (a major user of petroleum) did not use petroleum the U.S. would reduce its defence expenditures in the long run by between $1billion to 10 billion dollars per year. However, other authors such as Bohi and Toman, (1996) argue that there are good reasons why this expenditure should not be considered as part of the external cost calculations. These include the arguments that:

- Military expenditure is a cost of mitigating energy insecurity rather than a cost of insecurity itself
- Other national security interests are being served, not just oil
- Military presence is potentially on behalf of many other countries too

We are persuaded by these arguments to differing degrees; the first correctly identifies that the cost of doing something (preserving oil supplies) should not be interpreted as the benefit of that action. However, it may be interpreted as a minimum of what society is willing to pay for the benefit. The second and third arguments are correct and signal the practical difficulty of disentangling different types of security interests and associated expenditures for a wide range of countries when – as is most commonly the case – national defence expenditures are not published according to geographical reason or purpose. These practical difficulties have meant that within the constraints of the project resources we have not been able to include a military expenditure component in the estimation of energy security externalities.

Gas and Coal

The above section has looked at the energy security externalities related to the macroeconomic effects of oil price rises. It found that the small levels of electricity generation from use of oil in the EU imply that these externalities are very small. As table ? shows, gas, coal and nuclear power have much larger shares of the electricity generation so that price volatility of these may have significant effects.

Certainly, recent price movements of coal and gas from selected countries shown in Figure 5 and Figure 6, respectively, illustrate that such volatility exists.

Table 9. Fuel sources for electricity generation in the EU25 (%) (2004)

Energy fuel	Proportion of EU electricity generated from fuel (%)
Oil	4
Gas	19
Coal	31
Nuclear	31
Other	15
Total	100

Source: IEA Energy Statistics

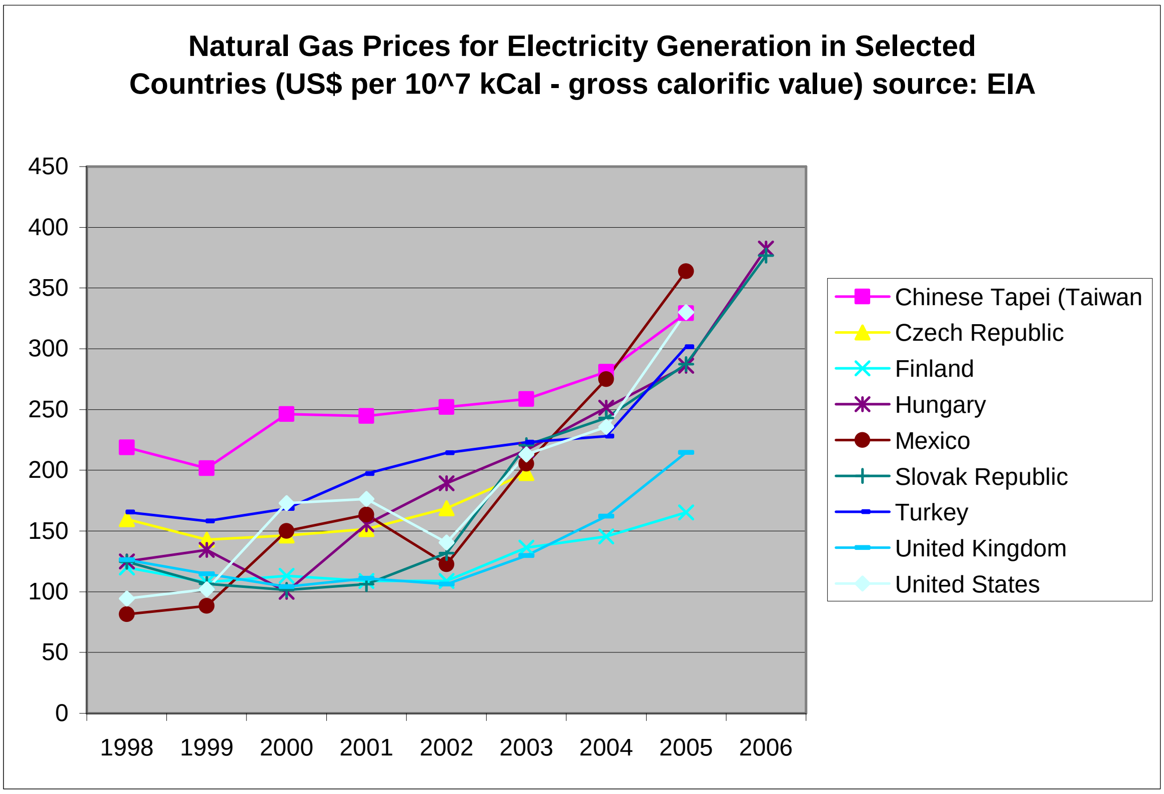


Figure 7- Natural Gas Prices for electricity generation in Selected Countries (US$ per 10^7 kilocalories, gross calorific value). Source EIA http://www.eia.doe.gov/emeu/international/ngasprie.html

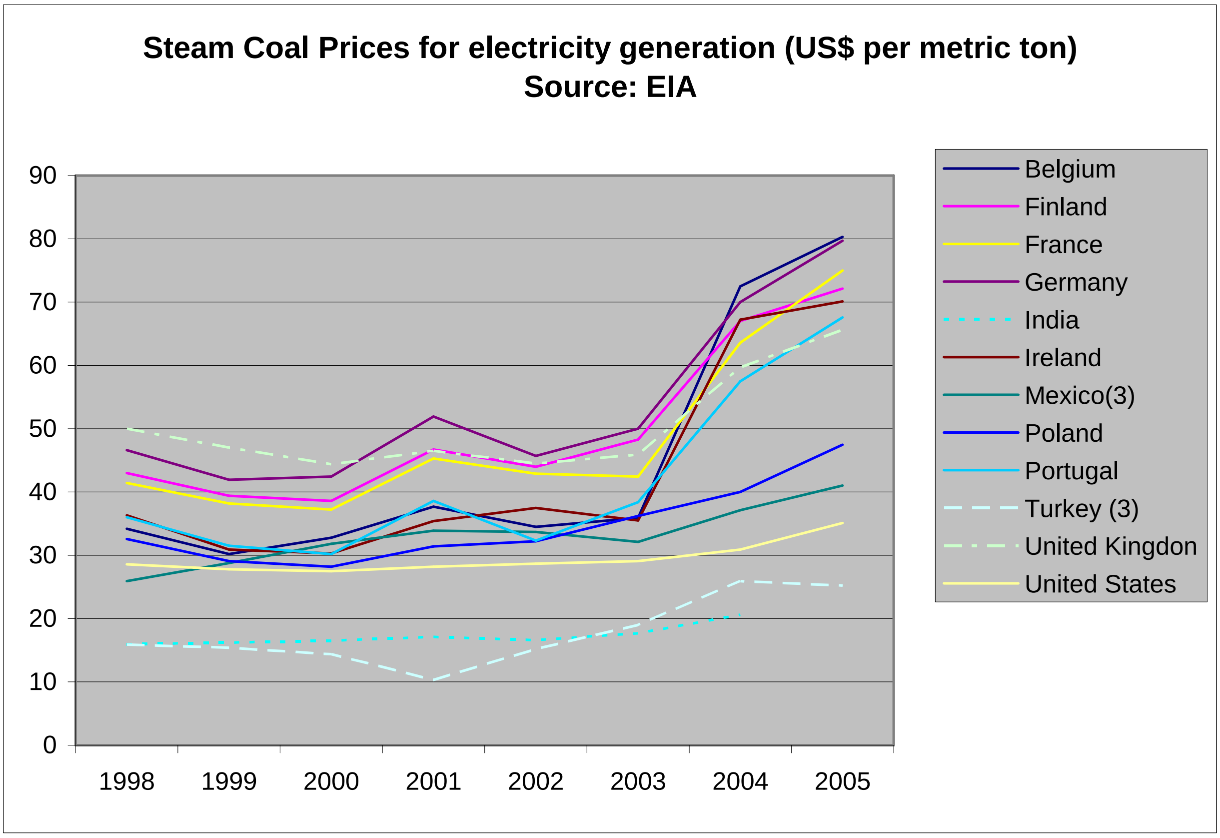


Figure 8: Steam coal prices for electricity generation (US$ per metric ton) Source: EIA.
http://www.eia.doe.gov/emeu/international/stmforelec.html

Russia, Algeria and Norway are the biggest three source countries for natural gas imports to the EU27 from 1999-2006, with Nigeria significantly smaller, whilst Russia, Australia and South Africa are the largest source countries for coal imports to the EU. However, whilst energy security risks from these fuels are well known, (see e.g.Stern, 2004a on possible causes of gas insecurity), to our knowledge, no quantitative analysis has been undertaken on the macro-economic – or other – sources of possible external costs from such risks. We highlight this as a research gap.

4. Overall Conclusions

Measurement of energy security externalities remains a complex and difficult exercise. Problems of definition as to what constitutes these externalities make agreement on what the policy issue is hazardous. Additionally, the range of assumptions that need to be made in order to calculate quantitative estimates of the size of these externalities means that these estimates should be viewed as indicative only. There are also a range of gaps in the coverage of the analysis, notably the exclusion of oil price volatility impacts, and the potential macroeconomic costs of gas and coal supply disruption, that suggest that the negligible values (around 0.000004 €/kWh) currently estimated are much lower than the true costs, whether categorised as external or not.

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Section 2 - An Overview of Selected Studies on the Value of Lost Load (VOLL)

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1. Introduction

The tripping of high voltage lines in Germany in 2006 had large consequences for electricity users throughout a significant part of Europe (UCTE, 2007). Earlier interruptions in power supply in Australia (2004) and in the USA, Scandinavia and Italy (2003) had similarly pervasive effects (IEA, 2005; Bialek, 2004). These events have focused the attention of energy planners in industry and politics, recently even more than before, on the importance of the reliability of electricity supply. More broadly, these instances of power supply interruptions have contributed to a wider discussion on the pertinence of energy supply security at large.

Security of energy supply has at least four important features: reliability, capacity, diversity, and dependency. All or at least a subset of these facets of energy supply security are usually distinguished in the literature on this subject matter (DTI, 2006). This report is only dedicated to security of *electricity* supply, as one of the essential topics in the more general theme of *energy* supply security, so we here focus mainly on the aspect of reliability. Reliability is interpreted as relating to both the production and the distribution network part of the total electricity supply chain. Measuring whether or not, and the extent to which, energy supply is secure, is not trivial. Quantifying security of energy supply is particularly difficult because no market for the quality of energy supply exists, or, inversely, a market for interruptions of that supply. One way of dealing with the quantification of security of energy supply is determining the reverse. It proves often easier to estimate the costs of the effects of supply interruptions for energy consumers than the value of situations in which no such interruptions occur. The cost of the impacts of supply interruptions, or value of security of energy supply, proves to be very different from the willingness-to-pay to avoid these interruptions. Still, a strong relationship exists between these two notions. The value of security of energy supply relates, naturally, to the level of the actual demand for the corresponding energy services.

As in this paper we focus on the power sector, we express the costs or 'value' of interruptions in the supply of energy (electricity) as the Value Of Lost Load (VOLL). The aggregate value of (in)security of electricity supply can thus be expressed by multiplying the probability of the intensity, frequency and duration of supply disruptions, i.e. the expectation value of the amount of electricity un-served, by this VOLL variable. While other variables are found in the literature as well, VOLL is our expression of reference throughout this report, the main purpose of which is to provide an overview of some of the most relevant recent VOLL-related references. In particular, section 2 below describes why we often observe a lack in security of energy supply, what the nature of this deficiency may be, and why a demand for security of energy supply exists. Section 3 points out what the factors are that determine VOLL, how VOLL can be measured, and what the relative (dis)advantages are of each of the different methods of measurement. Section 4 overviews a range of recent VOLL studies, links the information available from these studies to data on Gross Domestic Product (GDP), and stipulates VOLL ranges for developed and developing countries applicable in 2030. In section 5 we briefly speculate on how measures for the security of electricity supply, and hence levels of VOLL, may evolve in the future.

2. The rationale behind the demand for security of supply

We distinguish two types of demand for security of electricity supply: the demand for security of supply on production markets, on the one hand, and in transmission and distribution networks, on the other hand. While there are obviously linkages between these two categories, the demand for security of supply from the perspectives of production (section 2.1) and networks (section 2.2) are often presented separately, since the consequences of production and network failures (section 2.3), respectively, are generally very different.

2.1. Demand for security of supply on production markets

The literature often differentiates between three main kinds of market failure in the production market (see, for example, ECN/SEO, 2004; CPB, 2005):[3]

- Lack of transparency,
- Knock-on effects of supply interruptions,
- Free-riding of reserve capacity.

As for the first, electricity markets create rarely automatically full transparency. As a result of insufficient market transparency, power supply and demand may not be in balance. For example, the availability of production capacity deemed necessary is usually based on the prevailing peak demand. The latter, however, is determined by millions of independently made decisions that can never be predicted beforehand with complete certainty, implying a lack of transparency in the power market. Similarly, an even larger lack of transparency exists for the long term, as it is often exceedingly difficult to predict the development of electricity demand over a long time span. Aggravating this type of market failure is the fact that both short-term decisions related to e.g. maintenance of production capacity and long-term decisions on capacity investments are mostly taken by decentralized market parties. They usually possess imperfect information, in particular when customers make long-term contracts only to a limited extent. Also, if power producers have part of their supply capacity located abroad, their own supply potential may be unclear and subject to incertitude, because of fluctuations in cross-border transmission capacity and uncertainties in the availability of emergency power in the neighboring country under consideration.

The second source of market failure relates to the fact that a shortage in certain production capacity could lead to an interruption of other production capacity. The reason is that the demand becomes too high in proportion to the available supply, as a result of which the network frequency drops. If the network frequency starts deviating

[3] ECN/SEO (2004), p. 15-16; CPB (2005), p. 18-21. Sometimes additional types of market failure are mentioned, but these are closely connected to one of the three categories listed here.

too much from the frequency of the electricity delivered to the network, it will automatically be cut off from the network. This process can continue in a cascade of production capacity being cut off from the network as soon as their supply frequencies fall outside the acceptable network bandwidth. Such a knock-on effect resulted in the power supply interruption that lasted for days in the USA in 2003 and likewise in the nation-wide interruption in power supply in Italy that year (CPB, 2005).[4]

The third type of market failure relates to the reserve capacity usually complementing the core capacity. The liberalization of the electricity production sector has resulted in a declining reserve capacity, since producers want to keep their production capacity as limited as possible in order to increase their profits. From a social point of view, however, i.e. for society as a whole, it may be optimal to have more reserve capacity, in order to lower the probability and consequences of possible interruptions. In other words, reserve capacity (and security of supply in general) has public good characteristics, as for technical and economic reasons it is not possible to curtail all customers individually from using it, even when they are not paying for the services delivered by that reserve capacity. This follows from the non-excludability nature of reserve capacity.[5] In many cases there is thus free-riding of electricity consumers on reserve capacity.

Two characteristics of the electricity sector, on respectively the supply and demand side of the market, worsen these three forms of market failure. On the supply side, the fact that electricity is essentially not storable implies that production has to be flexible and quickly adaptable in order to meet demand fluctuating strongly over time. Production capacity should therefore not be over-constrained and reserve capacity is needed for circumstances with peak demand. On the demand side, a lack of information exists due to the absence of real-time metering and billing, as a result of which a large group of consumers does not pay the time- and location-dependent spot-price, but rather a price averaged over a certain period (e.g. a year), hence not differentiated over time and location. Consequently, electricity consumers such as households do usually not immediately face high prices when these are experienced by certain others. Households' electricity demand thus typically does not react correspondingly.

As opposed to households, large firms usually are subjected to real-time metering. For that reason, their marginal costs increase strongly when electricity prices suddenly increase as a result of e.g. a supply interruption. The marginal costs of electricity may exceed the marginal willingness-to-pay (WTP) of these firms, depending on the added value of the product they produce. In that case, these firms will probably halt their machinery and disconnect it from the network, in order to lower their electricity demand and limit the losses incurred as a result of the surge in electricity prices. Many large firms, however, often do not curtail their activities in the case of price hikes, because

[4] CPB (2005), p. 20.
[5] We here call a good non-excludable if it is either physically impossible or prohibitively expensive to prevent users from consuming it. Devices to curtail customers at a distance from consuming electricity are still very costly to apply on households.

curtailment costs may be high or the added value of their products or services elevated.[6] Overall, i.e. all consumers combined, electricity demand usually reacts only moderately to interruptions in supply. Power prices are therefore characterized by a steep increase when demand approaches the temporarily maximum supply.[7]

Because of these market failures, the objectives of producers may deviate from the objectives of society as a whole. In case the social costs of these failures are high, there is reason for government to intervene in the electricity production market. Although it is unclear whether or not market failures cause real and significant problems in practice, the political risks involved with non-intervention may be important, therefore justifying at least some level of intervention by government. Government may help incorporating VOLL-related externalities, whereby it can increase overall social welfare. The latter consists of the market value of electricity production plus the internalized associated externalities. Thus, from a social welfare perspective, the effects of investment decisions of producers on the probability and costs of interruptions should in principle also be considered. From a societal point of view, the demand for security of supply should also be part of producers' investment decisions. Government can play a role in stimulating producers to internalize VOLL externalities in their planning.

2.2. Demand for security of supply in transmission and distribution networks

Investment decisions for transmission and distribution networks are made by their respective operators, the transmission system operator (TSO) and distribution system operator (DSO). The investment decisions of both the TSO and DSO influence the probability of supply interruptions. Whereas the power generation market is today primarily free, at least in countries like those in the EU, networks are still strongly regulated because they are natural monopolies. In order to prevent monopolies from exerting market power, in most countries special power network regulation is introduced. These may for example be dedicated to hold down network tariffs, use fixed system charges, or involve prescribed levels of connection charges. Until recently, network regulation mostly focused on the prevention of monopolies, and did not strongly aim at achieving economic efficiency. Today, therefore also incentive regulation is being introduced in many countries in order to increase efficiency and reduce prices.

While this kind of regulation is likely to bring down prices for electricity, it also may create pressure on the quality of supply of electricity. Clearly, customers demand not only low prices but also quality of power supply. Therefore, incentive regulation is usually accompanied by and complemented with quality regulation. For quality regulation, demand for security of supply should be one of the factors determining network investments and hence investment decisions by TSOs and DSOs. Their

[6] It is possible that for cases of threatening production shortages these firms are contracted by the network operator to interrupt their power demand, in exchange for compensation that depends on the costs of the interruption. Market failure on both the production and network side may thereby be mitigated.
[7] See Figure 2 of SEO (2007).

decisions determine, or at least contribute to, the optimality of the quality of supply.[8] Without quality regulation, network operators may be focused too much on network costs only instead of overall social costs. In the case of networks, social costs are the sum of the costs of maintenance and upgrading the network for TSOs and DSOs (mostly for the latter these are together referred to as network costs), on the one hand, and the interruption costs for customers, on the other hand.

Today in many countries reliability standards are still based on past engineering practices and rules-of-thumb, instead of calculated optimal economic levels of quality of supply (Munasinghe and Gellerson, 1979). As a consequence, network quality may be too low, but also too high. In the last case, networks may be 'gold-plated' and the marginal benefits of investments in quality of supply for consumers smaller than the marginal costs they face. In the first case, the marginal benefits of additional network investments exceed the marginal costs. One of the inputs for quality regulation should be knowledge on the value of security of supply, or VOLL in particular, as information on these quantities is needed to determine the optimal level of network investments from a social welfare point of view (Ajodhia, 2006).

2.3. Consequences of production and network failures

The value of security of supply is strongly influenced by the cause of interruptions, since production failures usually have deeper consequences than network failures. A production failure may result in a real shortage of power, which strongly increases the price of electricity given that overall demand is unlikely to be significantly affected by the shortage and accompanying price rise. Indeed, electricity consumption is characterized by a low price elasticity. The case is different when a network failure occurs. With network failures, the entire system and all parties, that is, both suppliers and users of electricity, are affected at the same moment and in the same way, implying that prices typically change only modestly. Also, a break-down of parts of the network often does not imply a total interruption, because networks are built with redundancy and redirection of power streams can mitigate the ensuing problems. Therefore, consequences of network failures are usually smaller than those of production failures. In the case of a network failure it is not possible to make a distinction between customers who assign high value to electricity at that point in time and customers who attach lesser value or are able to more easily adjust their production or consumption pattern: all customers are equal and simultaneously affected in the same way. With the price increases experienced with production failures, on the other hand, those consumers that are real-time metered may decide to temporarily abandon their activities.

[8] Quality regulation usually necessitates benchmarking. An important precondition to implement benchmarking is that comparable companies are considered that have comparable operational conditions, such as related to soil, vegetation and weather characteristics. Because each country has usually only one TSO, benchmarking for TSOs calls for international comparison. Given the often very different operational conditions, international benchmarking is usually not trivial. National benchmarking as required for DSOs is typically more readily implementable. Quality regulation as referred to here therefore mostly applies to DSOs, rather than TSOs.

3. Value of Lost Load

Production and network failures both imply costs associated with the interruption in power supply. The latter can be expressed by the probability of an interruption multiplied by VOLL. VOLL is usually expressed, as in this report, in terms of the estimated total damage caused by not delivered electricity divided by the amount of electricity not delivered in kWh. Calculating VOLL as variable for quantifying supply interruption costs constitutes one of the important approaches towards evaluating security of electricity supply and provides insight in the value of security of energy supply at large. As many investment decisions in the energy sector are dominated by arguments regarding demand for security of supply, estimating the level of VOLL may be informative and even essential for justifying these decisions. The higher is the product of VOLL and the probability of supply disturbances, the more valuable are investments in generation and/or network capacity extension or improvement.

3.1. Factors determining VOLL

Since VOLL is determined by the costs of interruptions in power supply, we ask ourselves what the factors are that determine these interruptions. These factors are likewise responsible for the level of VOLL. Interruption costs prove to be highly variable, as a result of several facts or circumstances (see notably SEO, 2003; Ajodhia, 2006; DTI, 2006):

- *Differences between distinct types of customers.* The industrial sector, service sector and households, for example, face different electricity costs and differ in their dependency on electricity.[9] As a result, supply interruption costs for these sectors may significantly diverge. Interruption costs for the service sector generally tend to be higher than those for the industrial sector.

- *Differences in perceived reliability level.* The perceived reliability level influences the extent to which customers prepare themselves for potential interruptions. The higher the expected reliability level, the fewer precautionary measures (such as the purchase of power backup facilities) customers take. If an interruption occurs when the perceived reliability is high, costs are typically higher in comparison to a situation with a low perceived reliability. Although with lower perceived reliability levels the costs of a single interruption generally are less elevated, more interruptions are likely to occur thus resulting in a higher total damage. The reliability level is strongly determined by the incidence of interruptions in the past: the more structural interruptions took place previously, the lower the perceived reliability level. Perhaps surprisingly, even if the average number of interruptions is e.g. four per week (like in Nepal) or one per month (as in Brazil) customers may still perceive reliability to be high (Ajodhia, 2006). The probable explanation is that the perceived reliability varies with the

[9] Sometimes, types of customer groups are even further sub-divided. For example, Munasinghe and Gellerson (1979) distinguish twenty groups of customers.

dependency on electricity. The latter is connected to the standard of living. With higher levels of development and welfare, and hence a higher dependency on power supply, consumers become more critical and their attitude towards interruptions turns more unfavorable.

- *Differences in time of occurrence.* Interruption costs may vary significantly with the season of the year, the day of the week, and even time of the day at which the disturbance occurs. Naturally, for residential consumers winter interruptions usually lead to higher costs than summer interruptions. Another example, applicable to most sectors, is that a supply interruption occurring in the evening has typically more severe effects than one that happens during the night.

- *Differences in duration.* The duration of the interruption is of course also determinant for the costs incurred. At least for the industrial sector applies in principle that the longer the duration takes, the higher are the total costs experienced. While in some sectors duration and costs may be linearly proportional, in the industrial sector often the marginal costs decrease, that is, the longer the interruption the smaller the additional increase in interruption costs.

- *Differences in notification.* Advance notice about the occurrence and duration of an interruption lowers its consequences, since consumers may take preventive action or reschedule their original planning. According to NERA (2002), amongst others, it is often easier to give advance notice in case of production failures in comparison to when network failures occur.

As a result of these different facts and circumstances, VOLL does not adopt a single value, but rather can imply a large range of values dependent on the relative importance of these factors. These values can be expressed in a so-called customer damage function (CDF). CDF is a loss function dependent on these factors, which together determine the level of VOLL for a given set of factor values (such as the duration of a power outage and its time of occurrence).

3.2. Methods measuring VOLL

VOLL cannot be determined or observed directly from market behavior, simply because no market exists in which supply interruptions are traded. Still, VOLL may be determined indirectly. In the present literature on this subject matter, one can distinguish several distinct ways available to measure interruption costs and VOLL. We here distinguish four methods to estimate the effects of supply interruptions, thereby roughly (but not completely) following Billinton *et al*. (1993), CPB (2004), and de Nooij *et al*. (2007). These methods, that we subsequently briefly summarize, are:

- Revealed preferences (for example by market behaviour observations);
- Stated preferences (through e.g. surveys or interviews);
- Proxy methods (including the production function approach);
- Case studies (such as analyses of black-outs).

Revealed preferences

A revealed preference method may involve the financial means dedicated by a firm to the prevention of supply interruptions: these are indicative for the expected costs of these interruptions. At least two possibilities exist for reducing the effects of a power supply interruption: the installment of back-up power and the creation of interruptible contracts. As for the first, for example, from an economic point of view, there is a rule of thumb on how to decide on the optimal amount of investments in back-up power. The expected gain from a marginal unit of electricity in kWh self-generated by back-up power has to be equal at least to the expected loss of a marginal unit of electricity not supplied. Hence, the observable marginal costs of generating own electricity is an estimate for the marginal interruption costs (Ajodhia, 2006). For the second option a similar argumentation applies. Another revealed preference method uses power load data, for instance as determined by the load forecasting departments of utilities, to construct electricity demand curves. These demand curves can be used to calculate the consumer surplus loss, which in turn can be employed to estimate interruption costs.[10] The demand curve reflects the customer's willingness-to-pay for electricity services. Although not using electricity is not an option in many cases, it is sometimes possible to defer the use of electricity to another point in time, by which less can be paid for it. At points in time when the customer's willingness-to-pay is high, that is, when the price elasticity of demand is low, only a minor part of customer demand is shifted to another moment when a power supply disruption or interruption occurs, and the corresponding consumer surplus loss is relatively large. The revealed consumer surplus loss minus the bill savings is equal to the cost of the power supply interruption (Sanghvi, 1982).

Stated preferences

Two stated preferences methods can be distinguished: the contingent valuation method (CVM) and conjoint analysis (SEO, 2004).[11] When applying CVM, consumers have to indicate in a *direct* way how much money they are ready to pay for more reliability, i.e. their explicit willingness-to-pay (WTP), or how much money they want to receive in order to accept lower reliability of supply, i.e. their explicit willingness-to-accept (WTA). When conjoint analysis is performed, consumers have to show their preferences with regard to both reliability and electricity prices, by ranking and giving marks to a number of different situations or scenarios with varying assumptions on the prevailing characteristics and conditions of power supply and the distribution network. Customers can hereby provide in an *indirect* way a ranking between varying combinations of electricity prices and availability. Typically at least one of the situations has to contain a monetary value, like the reduction in the electricity bill that accompanies the outage.[12] A regression of the rating of scenarios is made, in relation to the features of the interruptions, for instance in terms of their frequency, duration, time of occurrence, and advanced notification.[13] From the resulting regression a utility function can be

[10] See Sanghvi (1982), p. 184.
[11] Both methods are based on evaluating the consumer surplus. Cf. Billinton *et al*. (1993), p. 97.
[12] CPB (2004), p. 42.
[13] SEO (2004), p. 50.

derived.[14] Values for the desirable monetary compensation per hour can be obtained by combining the utility function with other information on the customer's preferences.

Proxy methods

Proxy methods estimate interruption costs indirectly, through an inspection of variables that are closely related to the direct costs induced by power supply interruptions. In this context, the costs of lost production may be quantified explicitly, but also the costs resulting from e.g. overtime work, the costs associated with the restarting of machinery or the generation of materials waste (typically for firms), or the costs as a result of lost leisure time, spoiled goods, and stress (notably for households). The quantification of costs may not be trivial for households, because they do not produce market goods. Still, it is possible to relate power interruptions to lost leisure time, which can be quantified through the wage-differential that expresses the trade-off people face in their division of time between labor and leisure. People increase their number of working hours until the marginal value of labor, i.e. the wage rate, is less than or equal to the marginal value of leisure. In other words, the market value of free time can be approximated by the wage rate. Interruptions mean less free time, and the loss of leisure can be expressed in terms of the wage rate. Thus, supply interruptions can be quantified indirectly, since the free time lost can be monetized by multiplying the number and length of interruptions by the prevailing wage rate. Indirect costs may also result from emergencies like riots and looting, in the short term, or phenomena such as production reallocation, in the long term. The estimates of such effects for different production sectors and consumer groups can be aggregated to a macro-economic total. The ratio of GDP and the quantity of electricity consumed is considered to constitute an upper bound for the overall interruption costs, while the ratio of the electricity bill and the total consumption of energy may be considered a reasonable lower bound (Ajodhia, 2006).[15] The determination of interruption costs may or may not include linkages between sectors (De Nooij, 2007; ILEX, 2006).

Case studies

Interruption cost case studies involve the gathering of a wide variety of data and facts immediately after a large-scale power disturbance occurs. With these data, the costs of both production and network interruptions can be quantified, directly or indirectly. Simultaneously, other issues can be dealt with, quantitatively or qualitatively. Related questions that can be addressed in specific case studies, for example, are to what extent a nation is prepared to undergo large power disturbances from a societal point of view. This may become apparent in e.g. police and fire protection responsiveness to major power supply related calamities. Case studies may involve the consideration and listing of the different effects of a supply interruption in all fields of human activity. Each type of interruption impact may be associated with the economic value of that category and all cost contributions can be summed to obtain an aggregated value for the total interruption costs (Billinton *et al.*, 1993; Ajodhia, 2006; Nooij *et al.*, 2007).[16]

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[14] SEO (2004), p. 101-102.
[15] Ajodhia (2006), p. 84.
[16] Billinton *et al.* (1993), p. 96-97; Nooij *et al.* (2007), p. 280-281; Ajodhia (2006), p. 85.

3.3. Evaluating VOLL

These four methods each have their merits and drawbacks. In order to compare them, evaluate them, and, if needed, to make a choice between them, it is necessary to inspect their respective advantages and disadvantages. In the literature, the criteria used for assessing these different methods are: (1) their costs, (2) the accuracy of their results, and (3) the amount of information that can be acquired through them (Ajodhia, 2006).

Revealed preferences

Revealed preferences can be obtained from an inspection of e.g. the extent to which firms are prepared to deploy back-up power, or with consumer surplus methods. The first has as important advantage that it provides information derived from actual customer behavior that is generally relatively accurate. Using the amount of back-up power as revealed value for security of supply, however, possesses a few significant drawbacks. First, in developed countries back-up units and interruptible contracts are often used to only limited extent, given the high reliability of supply. Consequently, back-up power cannot be considered an appropriate indicator for the value of interruptions. Also, for e.g. hospitals the costs of interruptions are clearly more than the value of the back-up units. For that reason, the price of back-up power does not suffice in all circumstances, and may actually be an underestimation of the true value of security of supply. Furthermore, only large firms use back-up power, so this method cannot provide VOLL levels for small firms or households. The other type of revealed preferences method, the consumer surplus method, requires more data than for instance a proxy study. The results, however, do not necessarily improve proportionally, for at least three reasons. First, WTP applies to planned electricity consumption, which may not be the right indicator for WTP relating to unplanned interruptions. Second, this method assumes that more costly production capacity is used after all cheaper capacity has been deployed already. In other words, marginal interruption costs are assumed to rise. Therefore, if an interruption occurs and power demand diminishes, the most expensive power plant should normally be stopped first and only subsequently the cheaper ones. In practice, however, such a ranking seems hardly to be applied. Third, demand curves for electricity are not easy to derive, as electricity prices do not change frequently, especially for the network part of these prices.

Stated preferences

The analysis of stated preferences also aims at evaluating consumer surplus losses and is therefore linked to methods studying revealed preferences. Compared to proxy methods, the analysis of stated preferences is more customer-based, bottom-up, and therefore has the advantage of incorporating more directly individual customer preferences. The proxy method, on the other hand, determines preferences as those of the average customer. A main disadvantage of using stated preferences is that the setting up carefully formulated questionnaires can be a tough, time-consuming, and expensive task. The hypothetical character of stated preference studies often involves disadvantages additional to those of consumer surplus based analyses. Both CVM and conjoint analysis ask consumers for their valuation through questionnaires. As customers know that their answers may be used by policy makers, they often respond strategically. As a result, WTP figures are often equal to zero or much smaller than WTA values. This outcome not only results from strategic behaviour, but also shows the nature of consumer preferences and their psychological and social features, not rarely aiming for status quo and reflecting an aversion for financial loss. Consumers are shown to often value a favourable change less than they assess an unfavourable change of equal size (Ajodhia, 2006). A disadvantage particularly associated with CVM is the fact that customers of developed countries in general do not have much experience with power supply interruptions. For them it may be hard to value the quality of a secure electricity distribution network and they may find it difficult to monetize their experiences and values. Conjoint analysis typically prevents these types of disadvantages and is also less affected by strategical behavior of customers, as monetary values are determined indirectly rather than directly (SEO, 2004).

Proxy methods

Proxy methods have as main advantage that they require few and easily obtainable data. Still, they possess several significant disadvantages. First, determining the relation between the proxy and the interruption costs can be complex and time-consuming. Second, the valuation of interruption costs for households through the wage differential method is frequently criticized, because the wage rate constitutes only a rough estimate of the value of free time. Often this method yields an over-estimate of the interruption costs, due to e.g. the presence of union regulation and economic conditions like unemployment (Sanghvi, 1982; Billinton *et al*. 1993). Third, customers do not always use their leisure time when faced with a power outage, since other work-related activities can often be carried out during the interruption time instead. Likewise, not all production in the industrial and service sector is necessarily completely lost when supply disruptions occur. Fourth, the proxy method does not account for fluctuations in the value of free time: this value may change according to the time of the day, the season of the year, as well as the interruption’s frequency and advance notification. Household activities often vary substantially over these factors. Fifth, proxy methods often do not account for restart costs and damages encountered to equipment. Sixth, these methods usually assume that the causal relationship between outage duration and total interruption cost is linear, but this may well not be the case: often interruption costs diminish over time in relative terms, i.e. their marginal additional values (while being positive) decrease with the length of the interruption. Seventh, some proxy studies do not include the fact that all households do not consume their free time simultaneously. Hence the total loss experienced by consumers, if a power supply interruption occurs, may be smaller than a proxy method would suggest.

Case studies

Case studies have a number of advantages. First, they provide information derived from actual customer behavior and often involve high accuracy, while the costs derived from them appear reasonable in comparison to those obtained through other methods. Second, they deliver lots of detailed information about the different factors that influence the costs of supply interruptions. On the downside, however, is the fact that case studies are often more costly to undertake than proxy studies, as well as more expensive to perform than revealed preference studies based on analyses of the costs of back-up power deployment (Ajodhia, 2006). Also disadvantageous is the fact that case studies cannot usually be planned before a supply interruption actually occurs. Such planning would, if feasible, contribute to preventing certain analysis pitfalls and yield a clearer insight in the main characteristics of supply interruptions and the reaction of customers to these disturbances. Of course, by definition a single case study can never be fully representative for interruptions and their consequences in general (Billinton *et al*., 1993).

4. Country and sector dependency of VOLL

A comparison of interruption cost studies analyzing levels of VOLL in different countries can give instructions about the nature of the country-dependency of the value of security of supply. It proves that the levels of VOLL differ highly across different studies. The first reason is that one blackout may be very different from another, even if a single country or sector is considered, e.g. in terms of the number of customers affected, but also by the duration of power outages or the frequency of interruptions. Between countries large differences may occur of typical VOLL levels as a result of the characteristics and quality of the national transmission and distribution network, as well as the regulation features by which specific countries are characterized. Other sources of differences occurring between different VOLL studies may derive from whether or not they focus on specific countries, regions or sectors only, as well as the method they employ to calculate VOLL. As we saw in the previous section, the number of VOLL calculation methods is abundant. Also of relevance in this context are factors such as the types of customers that are considered, the way costs are averaged over different customers or sectors, and with what physical units or economic parameters VOLL levels are expressed. For example, costs may be expressed per duration of power outage or per kWh not supplied, and costs may be presented in different currencies and years of reference. Outage costs sometimes are normalized to the peak load of consumers or valued by the frequency of interruptions. While many studies report VOLL per kWh of non-delivered electricity, many others quote VOLL only as costs incurred depending on the duration of the blackout under consideration. Apart from these two most commonly used means of expression, still other ways for expressing VOLL are found in the literature. Regarding differences in years of reference and currencies used across different studies, it is sometimes challenging to choose the right inflation and conversion rates required to compare the results of these studies, especially when the investigated countries are characterized by large differences in living standard and purchasing power.

Figure 1 shows a cross-comparison of supply interruption costs, that is, levels for VOLL, for different countries, for respectively the residential sector (Figure 1 a), commercial sector (Figure 1 b) and industrial sector (Figure 1 c), as well as for the economy as a whole (Figure 1 d). All VOLL data, taken from Ajodhia (2006), are normalized per kWh non-delivered electricity and are expressed in (2004) US$. In an attempt to find clues behind the differences in VOLL observed across different countries, we plot these VOLL levels against the GDP per capita values for each country under consideration. GDP per capita figures are taken from IMF (2007). The VOLL data in Ajodhia (2006) are collected from a range of different studies for different countries. These individual studies often break down overall power consumption in several distinct customer groups or sectors, among which notably the residential, commercial, industrial and agricultural sector. Each of these individual studies also apply unique methodologies, that not rarely are fundamentally different from those applied in the others. One should thus be aware that the data presented in Figure 1 ought to be considered as indicative only, as their nature is often widely diverging as a result of different scopes and underlying methods of analysis and calculation.

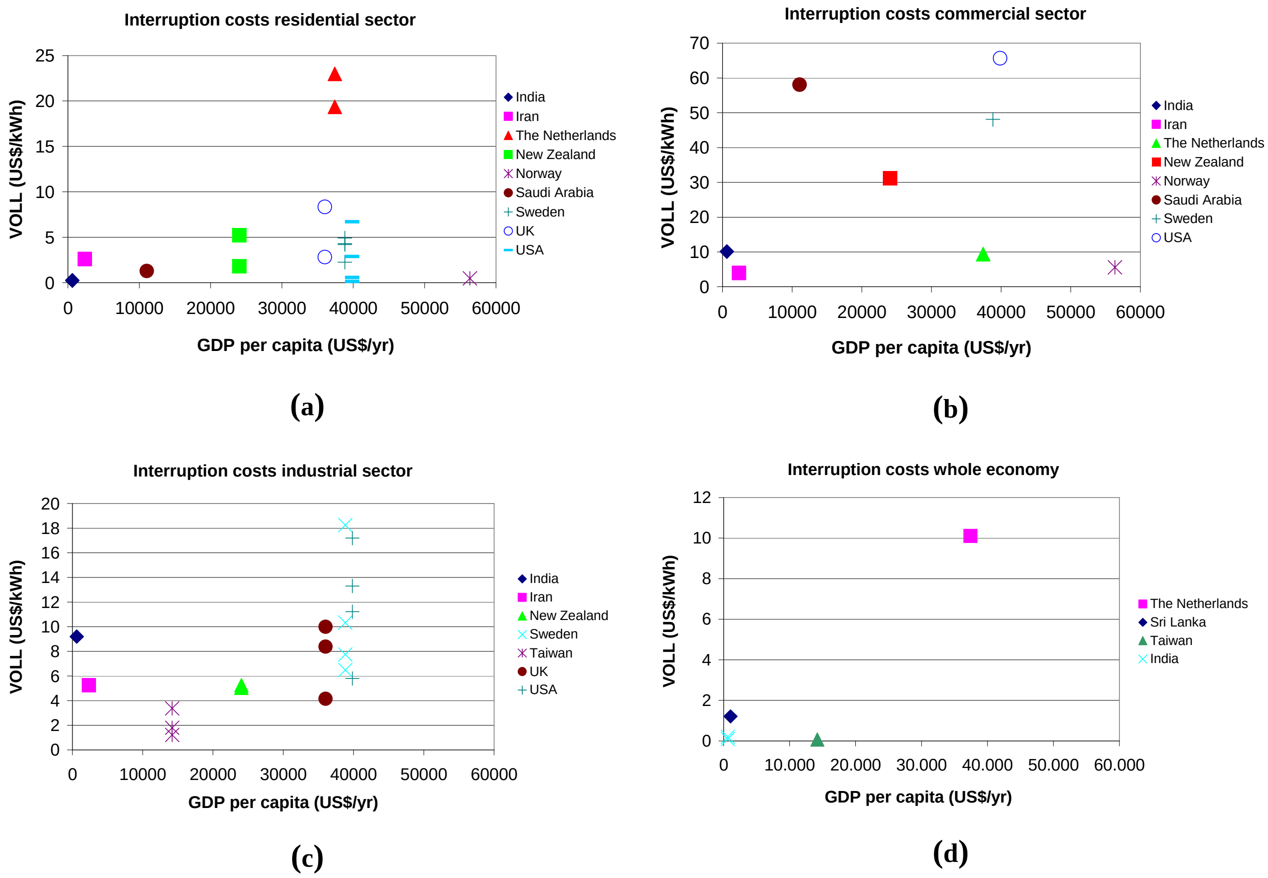

Figure 1. VOLL comparison for different countries, for the residential (a), commercial (b) and industrial sector (c), as well as for the economy as a whole (d). Costs are normalized per kWh non-delivered electricity and are expressed in (2004) US$. *Sources: Ajodhia (2006), p. 90-91, for VOLL data; IMF (2007) for GDP per capita data.*

First of all, we observe from Figure 1 that levels of VOLL depend significantly on the sector under consideration. We see that especially the commercial sector is highly sensitive to power outages, with VOLL reaching levels up to around 70 $/kWh. Also the residential and industrial sectors may be seriously affected by electricity interruptions, but less so than the commercial sector, typically up to values of some 25 $/kWh. Since VOLL applicable to an entire national economy averages interruption costs over all consumers involved – that is, including those whose activities are only moderately influenced by a short interruption or enduring blackout – economy-wide VOLL levels are generally significantly lower than those for each of the reported economic sectors.

Secondly, and preliminarily, given the caveats listed above, we may conclude from Figure 1 that for each of the three presented sectors, as for the economy as a whole, VOLL typically tends to be higher for countries with a relatively high GDP per capita than for those with a low per capita GDP. The main reason is that developed countries usually have a higher share of electricity to energy consumption, and are therefore generally more dependent on power supply, than developing countries. We also see that the spread in VOLL, and thus the 'risk' for a high level of VOLL, is higher for more developed countries than for developing ones. This can be seen particularly well in Figure 1 (c) for the industrial sector. Also in Figure 1 (a) for the residential sector this is rather clear, although one needs to bear in mind that the two outlaying values for the Netherlands are mostly explainable through the methodology used in the underlying analysis and the fact that leisure time is valued highly in that study, thus explaining the high impact of outages in particularly the residential sector. A similar observation can be made for Figure 1 (b) regarding the commercial sector. The only deviating data point is perhaps the one referring to Saudi Arabia, which can probably be explained by the uniqueness of its economy. Although few studies are available that bear on the economy as a whole, as can be seen from the few data points depicted in Figure 1 (d), one may also here make the careful conclusion that developed economies seem more sensitive to power supply interruptions, hence display higher levels of VOLL, than countries in transition or on a path towards economic development. The main reason is again that the former have generally been subject to more extensive electrification than the latter during their history of economic development, and have thus become more dependent on electricity and are thereby more affected by possible electricity outages.

As in the rest of the developed world, in both the US and in Europe the demand for electricity has increased steadily for the past decades. Yet transmission lines that transport power from generation plants to customers have often not been added or upgraded at the same pace. As a result, the grid in the US and in Europe has regularly become overloaded, making it more prone to blackouts. Indeed, power interruptions have risen in both number and severity. This was demonstrated in August 2003 when the northeast of the US was debilitated by a massive blackout, and similarly when within two months major blackouts occurred in several European countries, among which the UK, Denmark, Sweden and Italy. To avoid these kinds of blackouts the ageing transmission systems in especially the US need not only to be renewed and expanded, but the power grids also need to be made smarter, as much of the control system dates from the 1970s and is not good enough to track disturbances in real time or to respond automatically to isolate problems before they snowball. Estimates peg the overall economic loss from all US outages over the past years at $70-120 billion/yr

(Amin and Schewe, 2007). Assuming that on average consumers in the US, using a total amount of electricity of about 4000 billion kWh/yr, are affected by an aggregate power outage of 1-2 days/yr, one concludes that the corresponding VOLL as applicable to the entire US economy lays in the range of 3-12 $/kWh.

A study by ICF (2003) confirmed this range. It determined that the costs incurred as a result of the US power blackout from 14 to 17 August 2003 amounted to a total of $7-10 billion and that during this period an aggregated figure of over 900 million kWh was left unsupplied. Hence, in this case the corresponding level of VOLL amounted to some 7-10 $/kWh. The same study calculated that the total (direct plus indirect) unit cost associated with the outage in New York City in 1977 was about 4 $/kWh (ICF, 2003). Interestingly, these figures are all typically two orders of magnitude higher than the average customer retail electricity price, and figures for VOLL are therefore not to be confused with the willingness-to-pay for secure power supply. For example, customers are found to be willing to pay, on average, about 3 US¢/kWh more for a supplier that can guarantee no more than two 30-second outages per year compared to a supplier with four 30-minute outages per year (Goett *et al*., 2000). This estimate shows that customers are willing to pay considerably for the reduction of power outages. Unlike VOLL figures, however, willingness-to-pay numbers are typically of the same order of magnitude as, or less than, the customer retail electricity price. Since still relatively little is known about the benefits customers perceive resulting from increased reliability of power supply or avoidance of supply interruptions, attempts are undertaken to assess the value of supply reliability, e.g. by surveying how much different types of firms are willing to pay for avoiding power outages of certain lengths of time, or how much they negatively value in anticipation blackouts of given duration (Willis and Garrod, 1997). Willis and Garrod (1997) report VOLL figures for Finland in 1977 in the range of 1-4 £/kWh for industrial users, i.e. corresponding to some 2-8 $/kWh, with higher values for commercial users and lower values for domestic consumers.

A publication proposing a methodology for estimating the loss aversion from consumer survey data reports that the aggregate cost of unsupplied electricity during power outages in the Israeli household sector is about 7 $/kWh, in 1990 prices and with the assumption that 2 shekels = 1$ (Beenstock *et al*., 1998). This cost, however, varies strongly with the existing level of service, and there is considerable variation in the economic cost of outages by season, time-of-day and day-in-week. The corresponding expected cost range of unsupplied electricity is 1-11 $/kWh, depending on mostly the season and time-of-day. In an assessment of the economic value of lost load for the Electricity Commission of New Zealand, VOLL figures are quoted that are significantly higher, at about 20 and 30 $/kWh for New Zealand and Australia respectively (EC-NZ, 2004). The difference between these two numbers, developed with the same methodology, is largely due to the fact that the average consumer in Australia places a higher value on the continuity of power supply than one in New Zealand, especially in the residential and agricultural sectors. The interrupted energy rate or VOLL in Thailand has been determined to lay in a range of 40-80 Bath/kWh, hence amounting to some 1-2 $/kWh, for all consumers combined and regions averaged (ERI, 2001). This study confirms our observation that in lesser developed countries figures for VOLL are significantly lower than those in developed countries, sometimes differing by up to an order of magnitude.

Kariuki and Allan (1996) developed a method for calculating VOLL on the basis of data that reflect the perceptions of customers regarding the reliability of power services as well as their concerns regarding electricity supply interruptions. Subject to an extensive sensitivity analysis, and with different weighting methods (w.r.t. energy consumption vs. number of consumers), they find values for VOLL in the range of 2-20 £/kWh, that is, 4-40 $/kWh. With a similar purpose, but through a different methodology, Longo *et al*. (2006) investigate the willingness-to-pay of a sample of consumers (in Bath, England) for energy policy that, *inter alia*, affects the security of energy supply. They find that the residents under consideration attach high value to energy policy that brings private and public benefits in terms of (climate change mitigation and) energy security, and suggest that consumers are willing to pay a higher price for electricity in order to internalize the external costs associated with a lack of energy security. They do not, however, report on possible ranges of VOLL. In CIGRE (2001), on the other hand, a value of VOLL for Australia is reported of about 20 $/kWh, and for Canada of some 4-12 $/kWh. The same report suggests that similar figures for Great Britain are lower, ranging from 2-3 £/kWh, that is, 4-6 $/kWh, while in Norway energy-not-supplied is valued at approximately 3-4 $/kWh.

In Table 1 we report our personal estimates, based on the literature review described above, of the levels of VOLL in the year 2030. We do so by stipulating both a maximum range and an approximate 90% confidence level (CL) range, and emphasize that these are our personal guesses based on what we learned from our inspection of the references we found in the literature (see reference list hereafter). The depicted ranges reflect the envelope of all possible and different kind of uncertainties as summarized in the topology in the beginning of this section. Since our aim was to quote figures for 2030, we have slightly increased the present estimates for VOLL, in order to obtain numbers that are applicable in about two decades from now. We think such is necessary to reflect an increasing electrification worldwide, especially in the developing world, but also elsewhere, over the coming couple of decades. We believe it is safe to conclude that VOLL figures lay in a range of 4-40 $/kWh for developed countries and 1-10 $/kWh for developing countries. With about 90% confidence we can probably narrow these ranges down to, respectively, 5-25 $/kWh and 2-5 $/kWh. In principle we believe that the available data do not allow assigning probabilities to the specific values within these ranges. The data do seem to suggest, however, that they are left-skewed, that is, are skewed towards the lower values within each range, and thus have a median value that is closer to the lower bound than to the upper bound of the range in each of the cases. Certainly not enough data seem to be available to consistently distinguish between different levels of VOLL for different countries within the two broad categories listed.

Table 1. Levels of VOLL in 2030: maximum range and 90% CL range (authors' estimates based on literature review).

	VOLL entire economy in US(2007)$/kWh	
	Maximum range	**90% CL range**
Developed countries	4 – 40	5 – 25
Developing countries	1 – 10	2 – 5

5. VOLL and demand for security of supply in the future

In the preceding sections we have recapitulated how VOLL can be measured, have pointed out how important it may be to know the level of VOLL at any point in time for a given country, and have overviewed levels and estimated ranges of VOLL, today and in 2030, for both developed and developing countries. Can we further speculate on how VOLL may develop in the future? Two main considerations matter in any case in this context: (I) at present many developing countries are characterized by high rates of economic growth and concurrently increase their share of electricity consumption with respect to overall energy use, and (II) also countries in the industrialized world are still subject to increasing levels of electrification.

According to the IEA (2006a), electricity demand growth in a baseline scenario is on average 2.2%/yr between 2003 and 2050, making electricity the fastest growing component in total final energy demand. Electricity demand is expected to increases from 1433 Mtoe (16661 TWh) in 2003 to 4010 Mtoe (46631 TWh) in 2050.[17] This aggregated demand growth can be broken down in figures for different sectors. The residential sector is expected to show the highest growth rate (2.6%/yr on average between 2003 and 2050), followed by the service sector and the industrial sector (respectively 2.5%/yr and 1.8%/yr). Electricity's share in overall final energy demand is expected to increase from 16% in 2003 to 23% in 2050. These trends are mostly driven by a rapid growth in both total population and average income in developing countries, the continuous growth in especially electricity-driven industrial processes in developed countries, and the incessant increase in the number of electric devices used in homes and commercial buildings everywhere in the world.

As the demand for electricity of a country increases, the load and pressure on both generation capacity and distribution networks increases, and the country's dependency on reliable electricity supply rises correspondingly. Increasing electricity use, in developing and developed countries the like, implies larger production and network requirements, and hence a larger reliance on their continuous availability. The fact that worldwide absolute power consumption levels increase significantly over the decades to come makes that the aggregate potential detrimental effects of power supply interruptions increase as well. The observed and expected decrease of the electricity intensity – the electricity consumption per unit of GDP – by about 0.8%/yr in the period

[17] IEA (2006a), p. 73.

2004-2030 (IEA, 2006b)[18], may not positively affect the electricity dependency, since it is merely a reflection of a higher productivity and efficiency of electricity use. In fact, irrespective of whether a decrease in electricity intensity is matched to a reduction or not of a specific country's overall electricity needs as input to economic activity, a decrease in electricity intensity in principle makes electricity more essential. In absolute terms one could argue that the dependency on electric power of the country under consideration increases when relatively more output is generated with one unit of electricity. Since energy and electricity remain essential factors for economic productivity, a decrease of the electricity intensity is therefore not expected to increase the resilience of the economy to potential power supply disruptions – in absolute terms the economic damage caused by a unit of electricity-not-supplied should logically increase. Notably because of the more efficient use of electricity, it is the expectation that levels of VOLL on average will increase in the future for most countries in the world.

Of course, with economic development also the technical means are enabled to hedge for power supply interruption casualties. Indeed, countries increasingly attempt to neutralize their larger dependency on electricity by diversifying their fuel mix, expanding their power networks, extending their interconnection capacity with neighboring countries, and removing existing transmission network constraints. At the same time, this interlocking of networks also heightens the overall system risks each country faces. As a result, future disturbances may affect more strongly neighboring countries than previously was the case. One interruption can thus have larger implications than in a network that is less intertwined with other national or regional networks. It is difficult to derive one general clear picture that summarizes and captivates all these different trends and observations. We may safely conclude, however, that in case in a country the dependency on electricity increases, the 'value' that different sectors of the economy attach to an interruption in electricity supply also increases, as the number of alternatives that do not involve the use of electricity becomes smaller.

[18] IEA (2006b), p. 215.

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