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

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Abstract

This paper 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.

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):[1]

- 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 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

[1] 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.

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).[2]

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.[3] 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 curtailment costs may be high or the added value of their products or services elevated.[4] Overall, i.e. all consumers combined, electricity demand usually reacts only moderately

[2] CPB (2005), p. 20.
[3] 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.
[4] 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.

to interruptions in supply. Power prices are therefore characterized by a steep increase when demand approaches the temporarily maximum supply.[5]

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 decisions determine, or at least contribute to, the optimality of the quality of supply.[6] Without

[5] See Figure 2 of SEO (2007).

[6] 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.

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.

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.[7] 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 dependency on electricity. The latter is connected to the standard of living. With higher levels of

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

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.[8] 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).[9] 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.[10] 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.[11] From the resulting regression a utility function can be derived.[12]

[8] See Sanghvi (1982), p. 184.

[9] Both methods are based on evaluating the consumer surplus. Cf. Billinton *et al*. (1993), p. 97.

[10] CPB (2004), p. 42.

[11] SEO (2004), p. 50.

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).[13] 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

[12] SEO (2004), p. 101-102.
[13] Ajodhia (2006), p. 84.

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).[14]

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

[14] Billinton *et al*. (1993), p. 96-97; Nooij *et al*. (2007), p. 280-281; Ajodhia (2006), p. 85.

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.

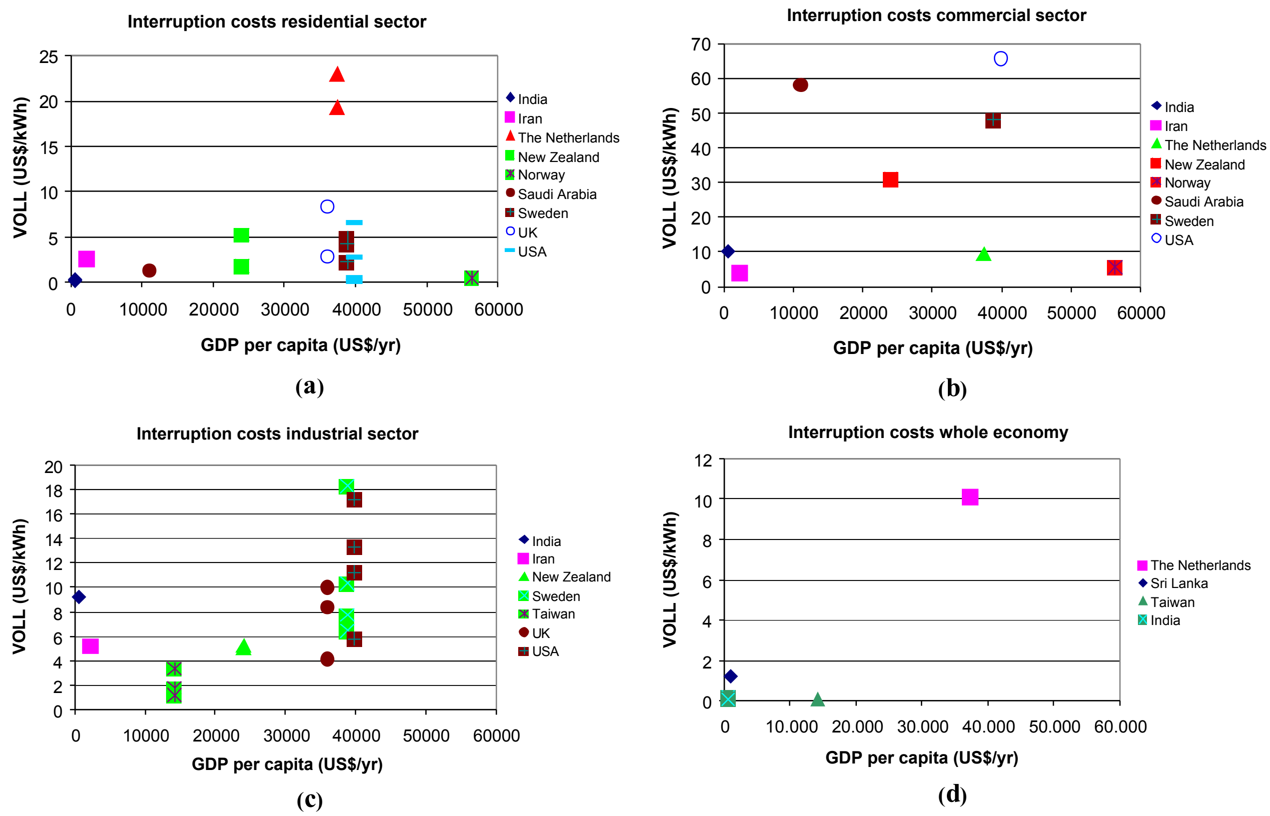

Figure 1. VOLL comparison for different countries, for the residential (a), commercial (b) and industrial sector (c), as well as for the economy as a whole (d). Costs are normalized per kWh non-delivered electricity and are expressed in (2004) US$. *Sources: Ajodhia (2006), p. 90-91, for VOLL data; IMF (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.[15] 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 2004-2030 (IEA, 2006b)[16], 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

[15] IEA (2006a), p. 73.
[16] IEA (2006b), p. 215.

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.

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