The Value of Lost Load (VoLL)

Methodology Statement Addendum A
Literature Review

29 July 2016

CONTENTS

VERSION HISTORY

Version	Date	Author	Status	Comments
1	14 June 2016	Impact research	Draft	
2	29 July 2016	T. Kennelly/ K. Quigley	Version 1	

APPROVAL

Name	Role	Date
Steve Cox	Head of Network Engineering	28 July 2016
Paul Turner	Innovation Delivery Manager	28 July 2016

GLOSSARY

Abbreviation	Term
CE	Choice experiment
CV	Contingent valuation
DECC	Department of Energy and Climate Change
DNO	Distribution network operator
GB	Great Britain
MXL	Mixed logit
Ofgem	Office of Gas and Electricity Markets
RIIO-ED1	Electricity distribution price control 2015-2023
SME	Small and medium enterprises
VoLL	Value of Lost Load
WTA	Willingness to accept
WTP	Willingness to pay

FOREWORD

The Value of Lost Load (VoLL) project will investigate if a single, uniform VoLL, applied to all customer segments, remains appropriate as Great Britain (GB) moves towards an economy increasingly reliant on electricity, driven by the decarbonisation agenda. Extensive customer research will build on previous research in this area to determine if a revised VoLL model would benefit customers.

The project is funded by the Network Innovation Allowance (NIA), introduced as part of the RIIO-ED1 price control, which provides an allowance for RIIO network licensees to fund projects which have the potential to improve network operation and maintenance and to deliver financial benefits to the licensee and its customers.

The project commenced in October 2015 and will be conducted over a 28-month period. It will culminate in a comprehensive assessment of how VoLL should be defined across a range of customer segments and ultimately inform a potential revised model to help distribution network operators (DNOs) better plan their network investment and customer strategies.

The key findings set out in this document specifically reference the learning from a literature review relating to the measurement of VoLL.

This report is one of a series of project dissemination documents and serves as an addendum to the VoLL methodology statement (version 2), which sets out the project research methodology and sampling approach that has been externally validated by an independent peer reviewer, Professor Ken Willis of Newcastle University.

The VoLL methodology statement (version 2) and its three addendums are available on the project webpage.

- *Methodology Statement Addendum A: Literature Review*
- *Methodology Statement Addendum B: Peer Review*
- *Methodology Statement Addendum C: Stakeholder Consultation.*

1 EXECUTIVE SUMMARY

1.1 Introduction

A literature review typically incorporates current knowledge including substantive findings, as well as theoretical and methodological contributions to a particular topic.

This literature review covers published work relating to the measurement of VoLL and, specifically, the methods considered most suitable for that calculation. This review draws on the comprehensive work undertaken by London Economics for the Office of Gas and Electricity Markets (Ofgem) and the Department of Energy and Climate Change (DECC) in 2013. This study made extensive use of stated preferences (what people *say* they will do) when measuring VoLL for domestic and small to medium enterprise (SME) customers. As noted in Section 2.4, the use of revealed preferences (what people *actually* do) would be the ideal information on which to estimate VoLL, but the lack of such data justifies the use of stated preferences in its place.

The analysis contained within this report has been used to inform the methodology utilised by Electricity North West. This approach has been validated and refined following an external peer review and key stakeholder consultation.

1.2 Summary of key findings

The key findings of the literature review are:

- VoLL must be determined by using scientific measuring techniques
- Willingness to pay (WTP) (derived from stated preferences gathered from customer surveys) is considered the most appropriate measure
- The limited availability of suitable revealed preference data makes the use of stated preference methods the most practical option for measuring VoLL
- Historically, it has been difficult to make meaningful VoLL comparisons across countries in the absence of a uniform framework
- A figure of £16,940/MWh was established by the London Economics work as the overall national average VoLL for domestic and SME customers. This is close to the value of £16,000/MWh established for RIIO by Ofgem
- It has been demonstrated that VoLL does vary by customer type
- Based on a high expectation of reliability, previous research indicates that customers object to having to pay more to improve the service they currently receive. However, they expect substantial compensation when that perceived reliability is reduced. Both results reflect an inherent customer bias to maintain the status quo.

1.3 Next steps

There will be ongoing learning as the project progresses and the approach will therefore be reviewed regularly to reflect any pertinent feedback and adapt to lessons learned.

2 RESULTS

2.1 Factors influencing VoLL measurements

There are significant challenges for researchers to determine the most effective method for measuring VoLL:

"Even if VoLL offers the opportunity of expressing the value of power supply security in monetary terms, there is no market on which power interruptions can be traded, which is why VoLL cannot be directly derived as market performance. Consequently, VoLL must be determined by using scientific measuring techniques."[2]

Studies conducted on how to measure VoLL fall into two broad types: a macro-economic approach (where the actual costs to customers and wider society are estimated) and WTP (derived from stated preferences gathered from customer surveys). A list of studies that have sought to measure VoLL is included in Appendix A.

The main observations that have been drawn from this review are:

- There is a wide diversity of VoLL values, ranging from a few €/kWh to as much as €45/kWh for private households and €250/kWh for industrial and commercial customers
- For private households, the VoLL values derived from WTP studies are generally significantly lower than those derived from macro-economic studies; for industrial and commercial customers they are generally higher
- The extent to which region is broken down influences the level of differentiation in VoLL values.

---

[2] Schröder and Kuckshinrichs, December 2015, Value of Lost Load: An efficient economic indicator for Power Supply Security? A Literature Review, Frontiers in Energy Research.

The result is that it is difficult to make meaningful comparisons across countries. To develop a uniform framework, Schröder and Kuckshinrichs recommend the following:

- Employ a single method (macro-economic or WTP)
- Clearly define the framework of the outage; the factors from Figure 2.1 must be given equal consideration
- Co-ordinate the breakdown of the industrial sectors both with respect to their delimitation and the degree of differentiation.

Inclusion of the factors listed in Figure 2.1 in the research will ensure a full understanding of how VoLL varies by the nature of the interruption and the situation of the customer.

Figure 2.1: Factors influencing power interruptions

Technical factors	Load-side factors	Social factors
Duration Region Frequency Time Dimension Advance warning Accustomed level of supply security	Type of electricity customer Number of customers affected and level of dependence on electricity Degree to which process steps can be substituted Existence of standby power supply	Special cultural and social features

Source: Rabatha et al, 2013[2] and adapted by Schröder and Kuckshinrichs, 2015[3].

Consideration will be given to the best method for presenting and analysing region. The third recommendation is of less relevance as it applies to industrial and commercial customers not covered in this project.

2.2 Overall VoLL and variations by time and segment

A figure of £16,940/MWh was established by the London Economics work as the overall national average VoLL for domestic and SME customers. This is close to the value of £16,000/MWh established for RIIO by Ofgem[4].

While the research suggested that VoLL remains consistent with the length of outage (ie the £/min is similar for a 20-minute outage as for a four-hour outage), it varies by time of day, day of the week and season of the year. It was also substantially higher for SME customers. These values are shown in Figure 2.2.

---

2 Ratha, A., Iggland, E., and Andersson, G. (2013). "Value of lost load: how much is supply security worth?," in Power and Energy Society General Meeting (PES), 2013, (Vancouver, BC: IEEE), 1–5.

3 Schröder and Kuckshinrichs, December 2015, Value of Lost Load: An efficient economic indicator for Power Supply Security? A Literature Review, Frontiers in Energy Research.

4 Ofgem, March 2011, Strategy for the next transmission price control - RIIO-T1: Outputs and incentives, Supplementary Annex.

Figure 2.2: VoLL by time

		Winter			Summer		
		Peak	Off-peak	Weekend	Peak	Off-peak	Weekend
Residential	WTA*	£10,289	£9,100	£10,982	£9,257	£6,957	£9,550
	WTP	£208	£315	£2,240	£105	£101	£2,766
SME	WTA	£35,488	£39,213	£44,149	£33,358	£36,887	£37,944
	WTP	£21,685	£21,325	£26,346	£20,048	£19,271	£21,864
Overall	WTA	£11,874	£12,144	£13,884	£11,036	£10,822	£12,070
	WTP	£5,082	£5,053	£6,827	£4,713	£4,556	£6,141

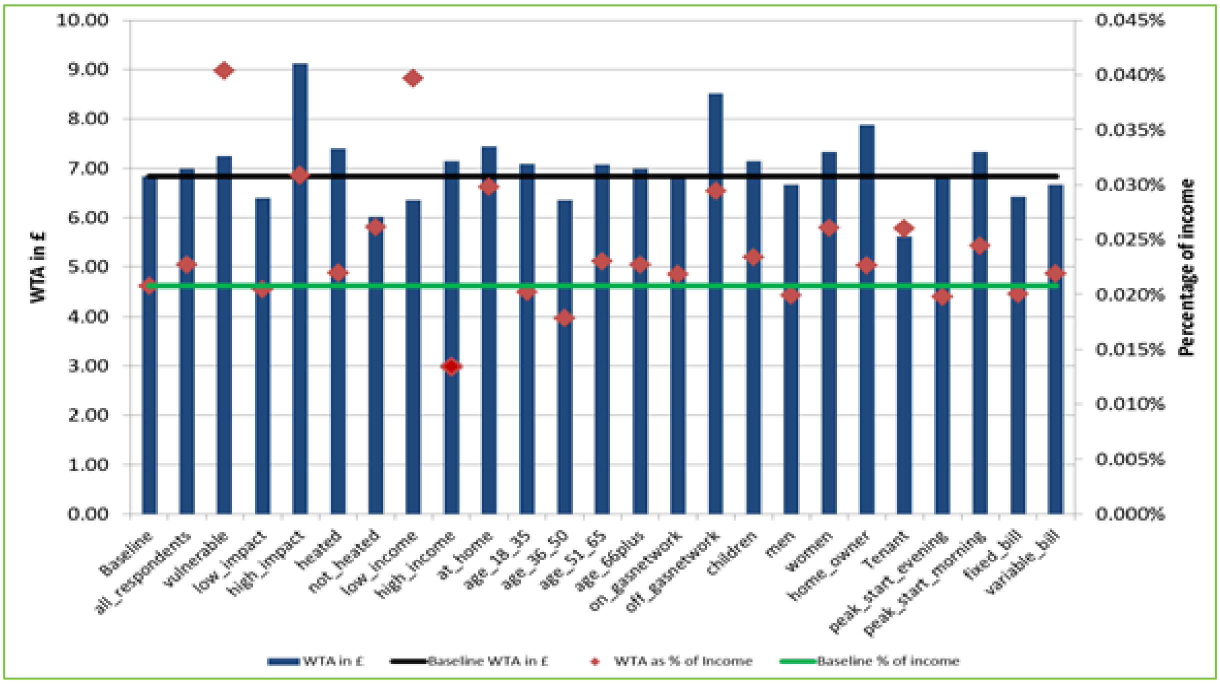
Source: Results of the London Economics report summarised in Royal Academy of Engineering, Nov 2014, Counting the Cost: The Economic and Social Costs of Electricity Shortfalls in the UK, A report for the Council for Science and Technology.

** Willingness to accept.*

This suggests VoLL is highest in winter at the weekends and lowest in summer off-peak. A single annual estimate should therefore represent a weighted sum of these values by outages experienced at these times over the year, in addition to an appropriate mix of domestic and SME customers.

VoLL is also seen to vary by customer type, as shown in Figure 2.3. This indicates that absolute WTA values are greatest for heavier consumers of electricity ('high impact' groups and those not connected to a gas network). The absolute WTA values for vulnerable customers and those on low incomes are near to values for the overall population ('baseline'), but when expressed as a proportion of their income, they are the highest (and correspondingly low for the higher income groups). This raises the issue of how to interpret VoLL in terms of social equity. Use of the absolute values could lead DNOs to focus on maintaining the reliability of supply for heavier consumers of electricity (generally more affluent users); use of values standardised against income reverses the picture.

Figure 2.3: VoLL by customer type



Source: London Economics, 2013, The Value of Lost Load (VoLL) for Electricity in Great Britain, Final Report for OFGEM and DECC.

2.3 Willingness to pay and willingness to accept

In research conducted on VoLL, customers consistently portray very different values according to whether this represents the WTA value for experiencing an outage, or the WTP value to avoid an outage. In the UK, WTA values can be five to ten times larger than WTP values[5].

In the UK, very high reliability of supply is the norm and VoLL is being measured in the context of existing supply provision. Based on this high expectation of reliability, previous research indicates that survey respondents object to having to pay more to improve the service they currently receive. However, they expect substantial compensation when that perceived reliability is reduced.

Both results reflect an inherent customer bias to maintain the status quo. Most studies have included both measures and presented them as upper and lower bounds within which the actual VoLL is likely to sit. A further consideration is whether the mean or median is the most appropriate reporting value, the former being the most common but the latter being advised where the distribution of an individual's values is skewed[6].

2.4 'Stated preferences' are the appropriate measure

'Stated preference' measures are market research techniques that present customers with a hypothetical market choice where it is possible to measure a trade-off between monetary measures and specific events eg 'pay £500 to avoid a one-hour peak outage'. Indirect methods, where respondents are not required to explicitly state a monetary value, but infer it through their choices, can provide a precise estimate of the monetary value of these events. These choices are entirely hypothetical; nevertheless, surveys that use carefully designed indirect methods are considered to give plausible and robust results, and their use is advocated by influential institutions such as the Council of European Energy Regulators[7].

The alternative to 'stated preference' measures are 'revealed preferences', in which the economic value of non-market goods can, in theory, be derived from the choices of individuals or businesses in the real world or responses to realistic experiments. In practice, it is very difficult to obtain data that sufficiently defines the true economic value of a particular event, such as an electricity outage. In the UK, for example, the majority of customers experience very few outages so data on their response is limited.

Even where data on such events is available, customers on a particular network cannot choose different service levels. Each customer is non-excludable and therefore susceptible to the same number of outages of the same duration although their experience of service reliability varies.

Hence, despite variations in the service experienced, there is no true revealed preference information on the *value* to customers of changes in the frequency of supply interruptions and in the duration of outages.[8]

A Royal Academy of Engineering report on the costs of electricity outages and how to measure VoLL[9] expressed the desirability of basing VoLL on revealed preferences and other 'real world' measures, but appreciated the difficulties involved in this. It noted that "*VoLL is not a value-neutral measure; it is a measure of people's perception of the value of a unit of electricity*". The report recognised that the work undertaken by London Economics was

[5] London Economics, 2013, The Value of Lost Load (VoLL) for Electricity in GB, Final report for OFGEM and DECC, p xi.
[6] London Economics, 2013, Value of Lost Load Literature Review and Macroeconomic Analysis, prepared for ERCOT, p20.
[7] Council of European Energy Regulators (CEER), Dec 2010, Guidelines of Good Practice on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances, Ref: C10-EQS-41-03.
[8] Information is available for a few industries on the value they place on supply interruptions, through their expenditure on replacement electricity, eg some London theatres have emergency generators in case of a supply interruption.
[9] Royal Academy of Engineering, Nov 2014, Counting the Cost: the Economic and Social Costs of Electricity Shortfalls in the UK, A Report for the Council for Science and Technology.

rigorous, but pointed to the potential for "*moving from stated preference methods for estimating VoLL to a combination of stated and revealed preferences, using data about how people actually act in the market for electricity security."*

It is therefore reasonable to conclude that the limited availability of suitable revealed preference data makes the stand-alone use of stated preference methods the most practical option for measuring VoLL, with the caveat that careful consideration is given to their application. This is reflected in the decisions taken by Ofgem in 2014:

"We have determined VoLL administratively (starting at £3,000/MWh and set to rise to £6,000/MWh by early winter 2018/19). This administrative VoLL is lower than the average domestic VoLL, average weighted SME and domestic VoLL and marginal SME VoLL according to the study we commissioned from London Economics, and therefore would not represent an appropriate cap."[10]

2.5 Choice experiments are the preferred survey method

There are several consumer research techniques that have been used to measure 'stated preference'[11]:

- Contingent valuation (CV) methods – respondents are asked directly about their WTP or WTA energy supply with a specific hypothetical reliability
- Direct worth – respondents are asked about the costs they estimate they would incur in particular scenarios
- Preparatory action method – respondents are asked to select from a list of options, which actions they would choose to mitigate the effect of a particular interruption
- Conjoint analysis – respondents are asked to choose between alternative scenarios of energy reliability, with each scenario having a specific cost associated with it.

Direct questioning, as represented by CV and direct worth techniques, does not generally work well with domestic customers. These techniques may require customers to make decisions about subjects with which they are unfamiliar and feel unqualified to take. The preparatory action technique, which involves questioning respondents about their behaviour in the event of an interruption, provides useful context and may be valuable in relation to future behaviour (see Section 10.3 in the VoLL methodology statement, version 2). However, the general practice in previous studies has been to ask customers to focus on the worst possible experience when considering outages, thus yielding potentially inflated VoLL values that might not be accurately representative of VoLL overall.

As a result, conjoint analysis, in the form of choice experiments (CE), is the method that is widely recommended and applied in the measurement of VoLL among domestic customers. This technique is considered most appropriate because it simply invites individuals to choose between competing alternatives, which is a type of decision that customers make on a regular basis in other markets[12]. Some SME customers may feel qualified to answer the direct questioning of CV, but the preference in the literature reviewed advocates using CE.

An example of a CE scenario from the London Economics study is given in Figure 2.4:

[10] Ofgem, May 2014, Electricity Balancing Significant Code Review – Final Policy Decision, p44.
[11] See Reckon, May 2012, Desktop Review and Analysis of Information on Value of Lost Load for RIIO-ED1 and Associated Work, p10.
[12] Ibid, p10.

Figure 2.4: Example of a CE scenario

	Option A	Option B
It lasts for:	20 minutes	Four hours
At this time of year:	Not winter	Winter
At this time of the day:	Off peak (10pm to 2pm)	Peak (3pm to 9pm)
On a:	Weekend/bank holiday	Weekend/bank holiday
The one-off payment you pay to avoid this happening	£15	£1

Please choose the option you prefer:
- Option A
- Option B
- Don't know.

Source: London Economics, 2013, The Value of Lost Load (VoLL) for Electricity in Great Britain, Final Report for Ofgem and DEC, p198.

The study described in this paper will use a similar stated preference (CE) methodology to the approach used by London Economics. This will ensure that results are comparable, based on an established and approved methodology. The work will build on the learning related to VoLL derived from stated preferences, including the stability of results over time (2016 versus 2013) and variations by geography and customer type.

3 CONCLUSIONS

The literature review in Section 2 assisted in identifying the possible methods of evaluation among customers and established best practice approaches to VoLL calculation, drawing on previous international work.

The literature review evaluated a stated preference, CE methodology recently utilised by London Economics which will form the foundation of the revised VoLL calculation. This will ensure that results are comparable, based on an established and approved methodology.

This review also directly influenced the methodology and will ensure that the project builds on the learning related to VoLL, derived from other international studies on the subject. This includes, but is not limited to, variations by customer type and low carbon technology adoption.

The draft methodology was subsequently refined in consultation with stakeholders and following an independent peer review. This addendum to the draft approach forms part of the revised VoLL methodology statement (version 2), published in July 2016.

4 NEXT STEPS

There will be ongoing learning as the project progresses and the approach will therefore be reviewed regularly to reflect any pertinent feedback and adapt to lessons learned.

5 APPENDIX A: SOURCES

Bibliography

This report has drawn primarily on the following sources:

Boyle Kevin, J., Özdemir, S., 2009. Convergent validity of attribute-based, choice questions in stated preference studies. Environmental and Resource Economics 42: 247–264.

Breffle, W.S., and Rowe. R.D., 2002. Comparing choice question formats for evaluating natural resource tradeoffs. Land Economics, 78(2): 298-314.

Brook Lyndhurst, August 2015, Uptake of Ultra Low Emission Vehicles in the UK: A Rapid Evidence Assessment for the Department for Transport.

Chilton, S., Lee, M.J., McDonald, R. and Metcalf, H. (2012) 'Does the WTA/WTP ratio diminish as the severity of a health complaint is reduced? Testing for smoothness of the underlying utility of wealth function', Journal of Risk and Uncertainty, 45(1), pp. 1-24.

Council of European Energy Regulators (CEER), Dec 2010, Guidelines of Good Practice on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances, Ref: C10-EQS-41-03.

Electricity Authority – Te Mana Hiko, 2012, Investigation into the Value of Lost Load in New Zealand – Summary of Findings.

London Economics, 2013, The Value of Lost Load (VoLL) for Electricity in Great Britain, Final report for OFGEM and DECC.

Ofgem, May 2014, Electricity Balancing Significant Code Review – Final Policy Decision.

Ofgem, March 2011, Strategy for the next transmission price control – RIIO-T1: Outputs and incentives, Supplementary Annex.

Plott, C.R. and Zeiler, K. (2005). The Willingness to Pay-Willingness to Accept Gap, the "Endowment Effect," Subject Misconceptions, and Experimental Procedures for Eliciting Valuations. American Economic Review, 95(3), pp. 530-545.

Ratha, A., Iggland, E., and Andersson, G. (2013). "Value of lost load: how much is supply security worth?," in Power and Energy Society General Meeting (PES), 2013, (Vancouver, BC: IEEE), 1–5.

Reckon, May 2012, Desktop Review and Analysis of Information on Value of Lost Load for RIIO-ED1 and Associated Work.

Royal Academy of Engineering, Nov 2014, Counting the Cost: the Economic and Social Costs of Electricity Shortfalls in the UK, A Report for the Council for Science and Technology.

Schröder and Kuckshinrichs, December 2015, Value of Lost Load: An efficient economic indicator for Power Supply Security? A Literature Review, Frontiers in Energy Research.

Strazzera, E., Cherchi E., Ferrini S. (2010). Assessment of regeneration projects in urban areas of environmental interest: a stated choice approach to estimating use and quasi option values. Environment and Planning A: 42: 452-468.

Train, K. (1998). Recreation demand models with taste differences over people. Land Economics 74(2): 230-239.

VoLL studies 2004-2014 – an overview

Study	State/ region	Base year	Method/scenario	Focus
Chowdhury et al.(2004)	USA – Midwest Region	2002	Willingness to pay: differentiation according to event, 2 s, 1 min, 20 min, 1 h, 4 h, 8 h	Industry, commercial users, private users, organisations
Bliem (2005)	Austria	2002	Macroeconomic approach: regional differentiation (federal states), consideration of different points in time (weekday/Sunday)	Industry (six sectors), private households
Centolella et al. (2006)	USA – Midwest Region	2005	Direct cost survey: differentiation into larger (>1 million kWh/a) and smaller (<1 million kWh/a) industrial and commercial users; determination for an interruption of 1 h, 2 h, 3 h, Willingness to pay	Industry (nine sectors), private households
Tol (2007)	Ireland	2005	Macroeconomic approach: for 2005, calculation differentiated according to 19 sectors; calculation of industrial VoLL from 1990 to 2005, but average values for industry broken down according to time of day/ week/year	Industry (19 sectors), private households
de Nooij et al.(2007)	The Netherlands	2001	Macroeconomic approach: differentiation according to regions, broken down according to days of the week (weekday/Saturday/Sunday) and time of day (day/evening/night)	Industry (six sectors), government, private households
Baarsma and Hop (2009)	The Netherlands	2003-2004	Willingness to pay: differentiation according to event: 1 event/a lasting 0.5 h,1 h, 4 h, 8 h, 24 h, and a 2-h event 1, 2, 4, 6, or 12 times/a year	Industry, private households
Sullivan et al. (2009)	USA	2008	Willingness to pay: a metadatabase was compiled from 28 studies (surveys on willingness to pay between 1989 and 2005); differentiation into large (>50,000 kWh/a) and smaller (<50,000 kWh/a) industrial and commercial users; differentiation according to length of event: short-term, 30 min, 1 h,4 h, 8 h; calculation for different points in time (summer/winter; weekday/weekend; mornings/daytime/evenings)	Industry (nine sectors), private households
Praktiknjo et al. (2011)	Germany	2002	Macroeconomic approach: combined with a Monte Carlo simulation	Industry (four sectors), private households
Leahy and Tol (2011)	Ireland / N Ireland	2008/ 2010	Macroeconomic approach: differentiated consideration of Ireland and Northern Ireland; period from 2000 to 2007, consideration of average values for industry broken down according to weekday/weekend; day/evening/night; spring/summer/autumn/winter	Industry, services, private households
Carlsson et al. (2011)	Sweden	2004	Willingness to pay: distinction between planned and unplanned; differentiation according to event 1 h, 4 h, 8 h, 24 h, consideration of the influence of socioeconomic factors; comparison before and after actual power interruption	Private households
Lineares and Rey (2012)	Spain	2008	Macroeconomic approach: for 2008, calculation differentiated according to 15 sectors; calculation of industrial VoLL from 2000 to 2008, but average values for industry for five sectors; differentiated according to Spanish regions for 2008	Industry (15 sectors), private households

Study	State/ region	Base year	Method/scenario	Focus
Zachariadis and Poullikkas (2012)	Cyprus	2009	Macroeconomic approach: differentiated according to seasons; weekday/weekend; time of day (hours); only industrial / commercial / private users are considered in the temporal differentiation	Industry (15 sectors), private households
Reichl et al. (2013)	Austria	2009	Macroeconomic approach: 12-h interruption in summer Willingness to pay: 12-h interruption in summer; consideration of the influence of socioeconomic factors	Industry (15 sectors), private households
Growitsch et al. (2013)	Germany	2007	Macroeconomic approach: results differentiated according to federal state and sector; overall costs determined for a period of 1 h for the federal states	Industry (15 sectors), private households
Röpke (2013)	Germany	2008-2010	Macroeconomic approach	Industry (five sectors), private households
Piaszeck et al. (2013)	Germany	2010	Macroeconomic approach: regional subdivision on the level of local districts; breakdown into time of day/course of the week	Industry (six sectors), private households
New Zealand Electricity Authority (2013)	New Zealand	2010	Willingness to pay: differentiation into small/medium-sized/large enterprises; regional differentiation; differentiation and event, 10 min, 1 h, 8 h; scenarios according to time of day and season	Industry, private households
Schubert et al.(2013)	Germany, Munich	2012	Willingness to pay: investigation of a blackout on 15 November 2012, duration 4 h	Private households
London Economics, (2013b)	UK	2011	Willingness to pay: differentiation into small and medium-sized enterprises/industrial and commercial enterprises; scenarios according to season and working day/weekend	SMEs, industrial and commercial enterprises, private households
Praktiknjo (2014)	Germany	2011	Willingness to pay: combined with a Monte Carlo simulation; blackout scenarios lasting 15 min, 1 h, 4 h, 1 day, 4 days	Private households
Kim et al. (2014)	South Korea	2010	Willingness to pay: differentiation according to event (1 s, 3 s, 1 min, 20 min,1 h, 2 h, 4 h, 8 h, 1 day, 3 days); at the same time socioeconomic factors also surveyed	Industry, private households

Source: Schröder and Kuckshinrichs, December 2015, Value of Lost Load: An efficient economic indicator for Power Supply Security? A Literature Review, Frontiers in Energy Research.

The following extensive bibliography is taken from: Schröder and Kuckshinrichs, December 2015, Value of Lost Load: An efficient economic indicator for Power Supply Security? A Literature Review, Frontiers in Energy Research.

Aichinger, M., Bruch, M., Münch, V., Kuhn, M., Weymann, M., and Schmid, G. (2011). Power Blackout Risks. Munich: Allianz Global Corporate and Specialty (AGCS) and The Chief Risk Officer Forum (CRO). Available at: http://www.agcs.allianz.com/insights/white-papers-and-case-studies/?c=&page=11.

Ajodhia, V. (2006). Regulating Beyond Price – Integrated Price-Quality Regulation for Electricity Distribution Networks. Delf: Delft University.

Ajodhia, V., van Gemert, M., and Hakvoort, R. (2002). Electricity outage cost valuation: a survey. Discussion Paper, DTe, The Hague.

Baarsma, B.E., and Hop, J.P. (2009). Pricing power outages in the Netherlands. Energy 34, 1378–1386. doi:10.1016/j.energy.2009.06.016

Barkans, J., and Zalostiba, D. (2009). Protection against Blackouts and Self- Restoration of Power Systems. Riga: RTU Publishing House.

Barth, T. (2013). "The German energiewende: shining or warning example for Europe? (Vortrag)," in 5th Conference ELECPOR, 2013. Lisboa.

Becker, G.S. (1965). A theory of the allocation of time. Econ. J. 75, 493–517. doi:10.2307/2228949.

Billinton, R., Tollefson, G., and Wacker, G. (1993). Assessment of electric service reliability worth. Int. J. Electr. Power Energy Syst. 15, 95–100. doi:10.1016/0142-0615(93)90042-L.

Bliem, M. (2005). Eine makroökonomische Bewertung zu den Kosten eines Stromausfalls im österreichischen Versorgungsnetz. Kärnten: Institut für Höhere Studien (IHSK).

Buldyrev, S.V., Parshani, R., Paul, G., Stanley, H.E., and Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. Nat. Lett. 464, 1025–1028. doi:10.1038/nature08932.

Bundesnetzagentur. (2007). Report by the Federal Network Agency for Electricity, Gas, Telecommunications, Post, and Railways on the Disturbance in the German and European Power System on the 4th of November 2006.

Carlsson, F., Martinsson, P., and Akay, A. (2011). The effect of power outages and cheap talk on willingness to pay to reduce outages. Energy Econ. 33, 790–798. doi:10.1016/j.eneco.2011.01.004.

Caves, D.W., Herriges, J.A., and Windle, R. J. (1990). Customer demand for service reliability in the electric power industry: a synthesis of the outage cost literature. Bull. Econ. Res. 42, 79–121. doi:10.1111/j.1467-8586.1990.tb00294.x.

Caves, D.W., Herriges, J.A., and Windle, R.J. (1992). The cost of electric power interruptions in the industrial sector: estimates derived from interruptible service programs. Land Econ. 68, 49–61. doi:10.2307/3146742.

CEER. (2010). Guidelines of Good Practice on Estimation of Costs Due to Electricity Interruptions and Voltage Disturbances.

Centolella, P., FARBER-Deanda, M., Greening, L.A., and Kim, T. (2006). Estimates of the Value of Uninterrupted Service for the Mid-West Independent System Operator. McLean: Science Applications International Corporation.

Chen, C.-Y., and Vella, A. (1994). Estimating the economic costs of electricity outages using input-output analysis – the case of Taiwan. Appl. Econ. 26, 1061–1069. doi:10.1080/00036849400000122.

Chowdhury, A.A., Mielnik, T.C., Lawion, L.E., Sullivan, M.J., and Katz, A. (2004). "Reliability worth assessment in electric power delivery systems," in Power Engineering Society General Meeting, 2004, (Denver: IEEE), 654–660.

de Nooij, M., Bijvoet, C., and Koopmans, C. (2003). "The demand for supply security," in Research Symposium European Electricity Markets, (The Hague).

de Nooij, M., Koopmanns, C., and Bijvoet, C. (2007). The value of supply security. The costs of power interruptions: economic input for damage reduction and investment in networks. Energy Econ. 29, 277–295. doi:10.1016/j. eneco.2006.05.022.

Deutsche Bundesbank. (2014). Euro-Referenzkurse der Europäischen Zentralbank – Jahresendstände und -durchschnitte.

Falthauser, M., and Geiß, A. (2012). Zahlen und Fakten zur Stromversorgung in Deutschland. Münch: Wirtschaftsbeirat Bayern.

Frontier Economics. (2008). Kosten von Stromversorgungsunterbrechungen. Essen: RWE AG.

Growitsch, C., Malischek, R., Nick, S., and Wetzel, H. (2013). The Costs of Power Interruptions in Germany – An Assessment in the Light of the Energiewende. Cologne: Institute of Energy Economics at the University of Cologne (EWI). Working Paper 13/07.

Holmgren, ÅJ. (2007). "A framework for vulnerability assessment of electric power systems," in Critical Infrastructure Reliability and Vulnerability, eds Murray A. and Grubesic T. (Berlin: Springer-Verlag), 31–55.

IEEE. (2004). IEEE Guide for Electric Power Distribution Reliability Indices. New York: IEEE, 1–50.

Kim, C.-S., Jo, M., and Koo, Y. (2014). Ex-ante evaluation of economic costs from power grid blackout in South Korea. J. Electr. Eng. Technol. 9, 796–802. doi:10.5370/JEET.2014.9.3.796

Kling, C.L., Phaneuf, D.J., and Zhao, J. (2012). From exxon to BP: has some number become better than no number? J. Econ. Perspect. 26, 3–26. doi:10.1257/ jep.26.4.3.

LaCommare, K.H., and Eto, J.H. (2006). Cost of power interruptions to electricity consumers in the United States (US). Energy 31, 1845–1855. doi:10.1016/j. energy.2006.02.008.

Leahy, E., and Tol, R.S.J. (2011). An estimate of the value of lost load for Ireland.Energy Policy 39, 1514–1520. doi:10.1016/j.enpol.2010.12.025.

Lijesen, M., and Vollaard, B. (2004). Capacity Spare? A Cost-Benefit Approach to Optimal Spare in Electricity Production. The Hague: CPB – Central Planning Bureau. CPB document No. 60.

Lineares, P., and Rey, L. (2012). The Costs of Electricity Interruptions in Spain. Are We Sending the Right Signals?. Vigo: Economics for Energy. WP FA5/2012.

London Economics. (2013a). Estimating the Value of Lost Load – Briefing Paper. Prepared for the Electric Reliability Council of Texas, Inc. Boston: London Economics.

London Economics. (2013). The Value of Lost Load (VoLL) for Electricity in Great Britain. London: London Economics, Ofgem and DECC.

Makarov, Y., Reshetov, V., Stroev, V., and Voropai, N. (2005). "Blackouts in North- America and Europe: analysis and generalization," in IEEE St. Petersburg PowerTech, (St. Petersburg: IEEE), 1–7.

Munasinghe, M., and Gellerson, M. (1979). Economic criteria for optimizing power system reliability levels. Bell Econ. J. 10, 353–365. doi:10.2307/3003337.

Munasinghe, M., and Sanghvi, A.P. (1988). Reliability of electricity supply, outage costs and value of service: an overview. Energy J. 9, 1–18. doi:10.5547/ ISSN0195-6574-EJ-Vol9-NoSI2-1.

New Zealand Electricity Authority. (2013). Investigation into the Value of Lost Load in New Zealand – Report on Methodology and Key Findings. Wellington: New Zealand Electricity Authority.

Pesch, T., Allelein, H.J., and Hake, J.F. (2014). Impacts of the transformation of the German energy system on the transmission grid. Eur. Phys. J. Spec. Top. 223, 2561–2575. doi:10.1140/epjst/e2014-02214-y.

Petermann, T., Bradke, H., Lüllmann, A., Paetzsch, M., and Riehm, U. (2011). Was bei einem Blackout geschieht – Folgen eines langandauernden und großflächigen Stromausfalls. Berlin: TAB – Technikfolgen-Abschätzung beim Deutschen Bundestag.

Piaszeck, S., Wenzel, L., and Wolf, A. (2013). Regional Diversity in the Costs of electricity Outages: Results for German Counties. Hamburg: Hamburg Institute of International Economics (HWWI). Research Paper 142.

Portney, R.P. (1994). The contingent valuation debate – why economists should care. J. Econ. Perspect. 8, 3–17. doi:10.1257/jep.8.4.3.

Praktiknjo, A.J. (2013). Sicherheit der Elektrizitätsversorgung – Das Spannungsfeld von Wirtschaftlichkeit und Umweltverträglichkeit. Berlin: Institut für Energietechnik, Fachgebiet Energiesysteme Berlin, Technische Universität Berlin.

Praktiknjo, A.J. (2014). Stated preferences based estimation of power interruption costs in private households: an example from Germany. Energy 76, 82–90. doi:10.1016/j.energy.2014.03.089.

Praktiknjo, A.J., Hähnel, A., and Erdmann, G. (2011). Assessing energy supply security: outage costs in private households. Energy Policy 39, 7825–7833. doi:10.1016/j.enpol.2011.09.028.

Ratha, A., Iggland, E., and Andersson, G. (2013). "Value of lost load: how much is supply security worth?," in Power and Energy Society General Meeting (PES), 2013, (Vancouver, BC: IEEE), 1–5.

Reevell, P. (2015). Turkey blackout: massive power outage plunges country into darkness. ABC News. Available at: http://abcnews.go.com/International/ massive-blackout-plunges-turkey-darkness/story?id=30024749.

Reichl, J., Schmidthaler, M., and Schneider, F. (2013). The value of supply security: the costs of power outages to Austrian households, firms and the public sector. Energy Econ. 36, 256–261. doi:10.1016/j.eneco.2012.08.044.

Röpke, L. (2013). The development of renewable energies and supply security: a trade-off analysis. Energy Policy 61, 1011–1021. doi:10.1016/j.enpol.2013.06.015.

Rose, A., Oladosu, G., and Salvino, D. (2004). "Regional economic impacts of electricity outages in Los Angeles: a computable general equilibrium analysis," in Obtaining the Best from Regulation and Competition, eds Crew M. and Spiegel M. (Dordrecht: Kluwer), 179–210.

Sanghvi, A.P. (1982). Economic costs of electricity supply interruptions: US and foreign experience. Energy Econ. 4, 180–198. doi:10.1016/0140-9883(82)90017-2.

Schlandt, J. (2012). Die Angst vorm Dunkel. Frankfurter Rundschau vom. Available at: http://www.fr-online.de/energie/stromausfaelle-die-angst-vorm-dunkel,1473634,19496664.html.

Schubert, D.K.J., von Selasinsky, A., Meyer, T., Schmidt, A., THUß, S., Erdmann, N., et al. (2013). Gefährden Stromausfälle die Energiewende? Einfluss auf Akzeptanz und Zahlungsbereitschaft, Vol. 63. Munich: Energiewirtschaftliche Tagesfragen, 35–39.

Sullivan, M.J., and Keane, D.M. (1995). Outage Cost Estimation Guidebook. San Francisco, CA: Electric Power Research Institute.

Sullivan, M.J., Mercurio, M., Schellenberg, J., and Sullivan, F. (2009). Estimated Value of Service Reliability for Electric Utility Customers in the United States. LBNL Research Project Final Report.

Tol, R.S.J. (2007). The value of lost load. ESRI Working Paper, 214. Dublin.

Van der Welle, A., and van der Zwaan, B. (2007). An overview of selected studies on the value of lost load. Working Paper, Energy Research Centre of the Netherlands (ECN). Amsterdam, 1–23.

Von Roon, S. (2013). Versorgungsqualität und -zuverlässigkeit als Standortfaktor. Energieeffizienz und Erneuerbare Energien im Wettbewerb – der Schlüssel für eine Energiewende nach Maß. Munich: Tagungsband zur FfE-Fachtagung FfE- Schriftenreihe – Band, 31.

Wirtschaftskammer Österreich. (2014). Inflationsraten. Available at: http://wko.at/statistik/eu/europa-inflationsraten.pdf.

Woo, C.-K., and Pupp, R.L. (1992). Costs of service disruptions to electricity consumers. Energy 17, 109–126. doi:10.1016/0360-5442(92)90061-4.

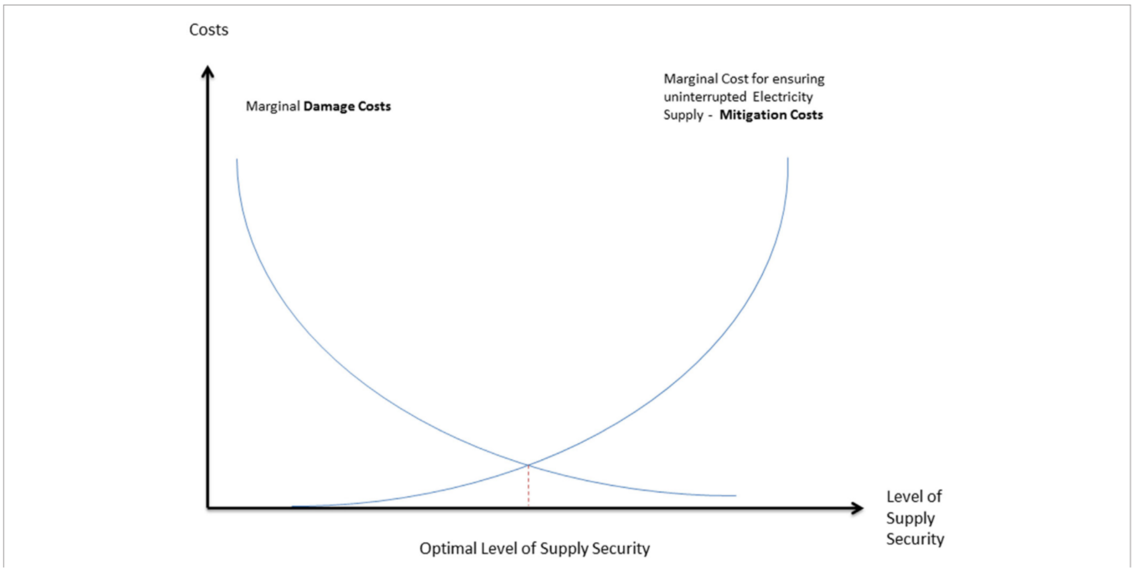
Zachariadis, T., and Poullikkas, A. (2012). The cost of power outages: a case study from Cyprus. Energy Policy 51, 630–641. doi:10.1016/j.enpol.2012.09.015.

6 APPENDIX B: ECONOMIC ANALYSIS, CHOICE MODELLING AND THE ESTIMATION OF WTA/WTP

Economic analysis of VoLL

As indicated by Schröder and Kuckshinrichs[13], VoLL represents the monetary damage costs arising from a power outage. The ideal level of supply ensures that the marginal damage costs equal the marginal costs for ensuring uninterrupted electricity supply, as illustrated in Figure 6.1.

Figure 6.1: Optimum power supply security



Source: Bliem, M. (2005). Eine makroökonomische Bewertung zu den Kosten eines Stromausfalls im österreichischen Versorgungsnetz. Kärnten: Institut für Höhere Studien (IHSK).

Where it is feasible, macro-economic approaches have been used to derive such a figure for VoLL indirectly. These comprise calculations of the actual costs incurred by customers as a result of supply interruptions, either in the form of actual monetary losses or as revealed in the way people respond (eg by running generators, paying for substitutions or repairs to damaged appliances). The main shortcomings of these approaches are that they are either too simplistic or the data is not sufficiently varied. Approaches that attempt to measure the costs incurred, such as the value of lost leisure time related to household income, can be too broad or subjective. Where 'revealed preferences' are the intended measure, the principle difficulty is that there are very few examples of actual outages that impact directly on consumer behaviour in developed countries.

The alternative approach of using consumer surveys to derive 'direct' estimates of VoLL use methods that measure precise values of the amount that consumers are willing to pay or accept in relation to avoiding or being compensated for outages. The drawback of this method is that the responses are hypothetical. The main concern relates to the realism of the *actual* values: *relative* values (eg that group A has a VoLL twice the value of group B) can be utilised with confidence.

There are two commonly used stated preference methods: contingency valuation (CV) method and choice experiments (CE). CV asks directly what a respondent would pay or want to receive in relation to a specific outage example, whereas CE presents a number of elements all varying at the same time. As argued by London Economics, CV is prone to bias

[13] Schröder and Kuckshinrichs, December 2015, Value of Lost Load: An efficient economic indicator for Power Supply Security? A Literature Review, Frontiers in Energy Research

in the form of respondents giving socially acceptable responses and/or answering strategically to influence the study findings. CE deters such responses because of the multiple trade-offs involved in each choice.

Choice models for stated preference studies

There is a substantial body of literature relating to the economic analysis of consumer demand and consumer choice[14]. All approaches look to the underlying principle of utility maximisation as a model of consumer choice. That is, individuals choose between competing alternatives (eg car versus bus versus train) the one from which they shall derive the greatest 'utility' (or least 'disutility').

This utility is composed of a number of elements related to each alternative, some of which are observable to the researcher (eg price, journey time) and some of which are not (eg habit, misperception). The presence of this unobservable component leads to the concept of 'random utility' where appropriate assumptions about the distribution of this component have allowed the development suitable stochastic choice modelling techniques (eg conditional logit). The addition of simulation methods related to increased computing power has extended such models to cope with heterogeneity between consumers (eg 'mixed' logit models).

In the context of measuring VoLL, mixed logit models provide the basis for measuring consumer choices as a function of different levels of supply interruption and service disruption, with different levels of compensation or cost.

In a stated preference study, such as a CE, it is assumed that individuals are rational, know their own preferences and, are able to choose that which offers them the highest utility. Thus, if an individual *n* is assumed to choose alternative *i* over alternative *j,* if the utility derived from attribute bundle *i* is greater than the utility derived from attribute bundle *j*; i.e. if $U_{ni} > U_{nj}$, where U_{ni} is the total utility associated with alternative *i* and U_{nj} is the total utility associated with alternative *j*. The utility function for respondent *n* related to alternative *i* is specified as:

$$U_{ni} = \beta_n x_{ni} + \varepsilon_{ni}$$

Where $\beta_n x_{ni}$ is the systematic (non-stochastic) utility function observed by the analyst because it is linkable to the attribute levels of each alternative (e.g. electricity service attributes, etc.) and ε_{ni} is a random component, which is known to the individual, but remains unobserved to the analyst. This random component (ε_{ni}) arises either because of randomness in the preferences of the individual or the fact that the researcher does not have the complete set of information available to the individual (Train, 2003).

A mixed logit (MXL) model will be used in the analysis, because unlike conventional logit models, it expresses choice probability as the probability that person n chooses alternative *i*, conditional on β_n. This is the standard logit formula:

$$L_{ni}(\beta_n) = \exp(\beta_n x_{ni}) \,/\, \Sigma_j \exp(\beta_n x_{nj})$$

Where L is the likelihood of respondent *n* choosing option *i* and *j* is all the alternative options. However, since β_n is random and not known, the (unconditional) choice probability is the integral of this logit formula over the density of β_n:

$$P_{ni} = \int L_{ni}(\beta).f\beta \,|\, \theta.d\ \beta_n$$

[14] McFadden, D, 1980, Econometric Models for Probabilistic Choice Among Products, The Journal of Business, Vol. 53, No. 3, Part 2: Interfaces Between Marketing and Economics (Jul 1980), ppS13-S29; Train, K, 2002, Discrete Choice Methods with Simulation, : Cambridge University Press; Juan de Dios Ortúzar1 and Luis G. Willumsen, 2011, Discrete Choice Models in Modelling Transport, Fourth Edition, John Wiley & Sons Ltd.

Hierarchical Bayesian analysis will be used to estimate the parameters of the MXL model. It is hierarchical because the approach has two levels. At the higher level, it is assumed that individuals' part worths are described by a multivariate normal distribution. At the lower level, it is assumed that, given an individual's part worths, his/her probabilities of choosing particular alternatives are governed by a multinomial logit model.[15]

Once the mixed logit model is estimated, the marginal WTA and WTP estimates are computed directly from the model specified. The ratio of the following two coefficients yields the WTA for the attribute ‘i’:

$$WTA_{\text{Attribute } i} = \beta_i / \beta_{price}$$

This assumes a linear-in-the-parameters model with no interactions, otherwise more complex calculations apply. Given the evidence from previous studies, no symmetry will be assumed between WTP and WTA and so results will be reported for both. The expectation is that WTP will be considerably lower than WTA.

In addition to utilising a mixed logit model in the analysis to account for heterogeneity in customer preferences further to observations made in the Peer Review, we shall also estimate standard conditional logit models to allow direct comparison of the results with the work undertaken by London Economics[16].

[15] The Sawtooth CBC/HB package will be used to estimate the model parameters for this study.

[16] London Economics, 2013, The Value of Lost Load (VoLL) for Electricity in Great Britain, Final report for OFGEM and DECC.