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Estimating the socio-economic costs of electricity supply interruptions

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Executive summary

Security of power supply is a crucial element of energy system planning and policy. However, the value that society places on it is not clearly known. Assessing the socio-economic costs of interruptions is an important first step to determining socially optimal levels of interruptions. Such an assessment needs to go beyond a pure focus on economic losses, but needs to include the costs of inconvenience for consumers. Available methods to quantitatively and qualitatively evaluate the effects of a supply interruption are discussed and compared. The importance of considering specificities of geographical location and time of interruptions is highlighted through case studies. Decentralised generation through renewables may help minimise the costs of interruptions by reducing the number of consumers affected. The role of decentralised storage options, demand response, and prioritisations of loads is discussed in this context. Since end-user preferences are not an integral part of a utility's planning process, expenses to avoid interruptions are disconnected from what end-users would be willing to pay for. This is economically inefficient for the society as a whole.

Power supply in the EU is characterised by a relatively high reliability. However, the reliability we experience today should not be taken for granted given the increasing shares of variable electricity generation, but also new opportunities to engage consumers through Smart Grids – and interrupt their supply as needed. Choosing the ideal level of reliability to aim for requires a thorough understanding of the socio-economic costs of electricity supply interruptions, which may be very different depending on timing and type of consumer. For example, while a household may not notice an interruption during office hours, a company unable to electronically submit a tender in time might potentially lose millions. However, the actual damage to society might just be less than the additional cost for a more expensive, but potentially better tender.

Estimating the socio-economic costs is a non-trivial task, yet required to determine socially optimal levels of interruptions. Such levels would ensure that investments to increase the system's reliability are balanced with the associated financial benefits, i.e., the reduced costs due to fewer and shorter interruptions. However, most reliability studies focus on suppliers. The value that society places on reliability is not clearly known across the EU. Also, the current distribution of costs between stakeholders lacks a causal link between those in charge of ensuring the power system's reliability and those having to bear the consequences of an outage.

Currently, historic reliability levels may be used to design the future power system. These may be quantified by defining an acceptable Loss of Load Probability (LOLP), which specifies the share of time when a generation shortfall may occur. Other design criteria are redundancy measures to ensure the system can cope with an outage in essential supply infrastructure (e.g., N-1 rule). Both approaches have in common that they do not build on quantifications of the impacts of interruptions on individual consumers or consumer categories. Thus, both

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approaches will not result in a socially optimal level of interruptions.

A clear understanding of the socio-economic costs of interruptions across the EU would be an important step to decide on such an optimal level. This brief provides guidance on how to value the consequences of supply interruptions and thus determine the demand for security of electricity supply.

Characterising interruptions

Prior to estimating the costs of interruptions, it is useful to understand the reasons why the consequences of supply interruptions differ from one to another:

- Firstly, there are different types of end-users in the electricity system. An interruption in a hospital has very different consequences than one in an industrial plant or household.
- Another important aspect is the time of occurrence of the interruption. The type of activity that is interrupted is dependent on the time of day, week and season. E.g., for a household, an interruption at 8 p.m. may interfere with recreation (e.g. television, internet), while at 3 a.m. an interruption typically has much smaller effects.
- In addition to the time of occurrence, the duration of an interruption also significantly influences its impact. Certain types of damage, such as the loss of computer files, occur instantaneously. Others, such as the loss of working hours and the spoilage of food, are proportional to the length of the interruption and may only occur after a certain delay.
- Advance notification of an electricity interruption also helps in mitigating its negative implications. For example, if one is made aware of an electricity interruption, they may avoid using an elevator. Further, if electricity supply is interrupted on a regular basis, people may prepare for it even without advance notification. While this may reduce the cost per interruption, the overall impact of electricity supply interruptions will be larger (e.g., less confidence of industry in the reliability of the system).
- This relates as well to the "perceived reliability level": the higher the perceived reliability in the affected area, the less firms and households are inclined to take precautionary measures (e.g., invest in backup facilities), and the greater the damage caused by an interruption (known as the 'vulnerability conflict').
- Also of importance is the source of the outage: an outage caused by a failure in the network may have smaller price effects than an outage caused by a shortage in generation, due to a higher redundancy in the grid.

Resulting electricity price increases can lead to large transfers of wealth from users to suppliers. While these transfers of wealth are not necessarily a social cost, they must be considered in policy-making[1].

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Composition of costs

Typically, cost information can be inferred from a market. However, currently consumers have no option to choose the tariff they pay depending on the level of reliability they receive. Thus, grid operators lack information on the value of reliability improvements and, in unbundled markets, utilities lack balanced incentives to engage in related investments.

In the absence of market mechanisms, assessments of the costs of interruptions are required. Various types of costs need to be considered, including direct infrastructure costs and indirect costs, such as production outages. In addition, macro-economic long-term costs related to market adjustments may occur, e.g., due to changes in the choice of business locations or investments in back-up generation.

Households: For households, only a part of the costs can be directly related to the household expenses, e.g., to replace spoiled food. Indirect, immaterial costs equally require consideration. These may include fear (e.g., to walk in an unlit neighbourhood), inconvenience (e.g., freezing), and the loss of leisure time (e.g., missing the championship's final). To assess the costumer's desire for security of supply commonly the Willingness-to-Pay (WTP) is being quantified, as further outlined below.

[1] Michiel de Nooij, Carl Koopmans, Carlijn Bijvoet, "The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks". Energy Economics 29, 2007, p. 277 – 295.

Industries and commercial services: There are primarily four sources of indirect costs of power outages in industries and commercial services[2]. First, their output will be affected leading to a loss of profits. Second, power outages can result in a loss of productivity during the outage and when restarting production/operations after an interruption (e.g., recovering unsaved computer files). Third, materials and/or equipment can be damaged by an electricity outage (e.g., dyeing in the textile industry, aluminium smelting). Fourth, there may be costs of labour required after a power outage. For instance, additional labour is sometimes required to restart production for which overtime bonuses may have to be paid. Long-term costs like a loss in reputation due to production delays are often neglected.

Quantifying costs

Several methods are available to quantitatively evaluate the effects of a supply interruption[3,4]. These include the following:

1. Surveys/interviews (stated preferences): In general, the costs of interruptions may be measured by estimating the value of lost load (VoLL). One method to determine this value is to ask people how much damage they have suffered due to supply interruptions, how much they are willing to pay (WTP) for a given reduction in interruptions, the minimum amount of money they are Willing-to-Accept (WTA) as compensation for an increase in interruptions, or which combination of electricity price and number, duration and timing of interruptions they prefer (conjoint analysis)[5,6]. The latter may also be referred to as choice experiment. When carried out in Sweden, such a study showed that marginal WTP of households to reduce power outages increases with duration, and is higher during weekends and winter months[7]. This is confirmed by a study in Austria, which found that the WTP is 33% higher in winter than in summer[8]. On a yearly average, values ranged from €1.4 to avoid a 1 hour power cut to €17.3 to avoid a 24 hour interruption.

Table 1 summarises and compares the VoLL for households from past survey-based studies in different countries.

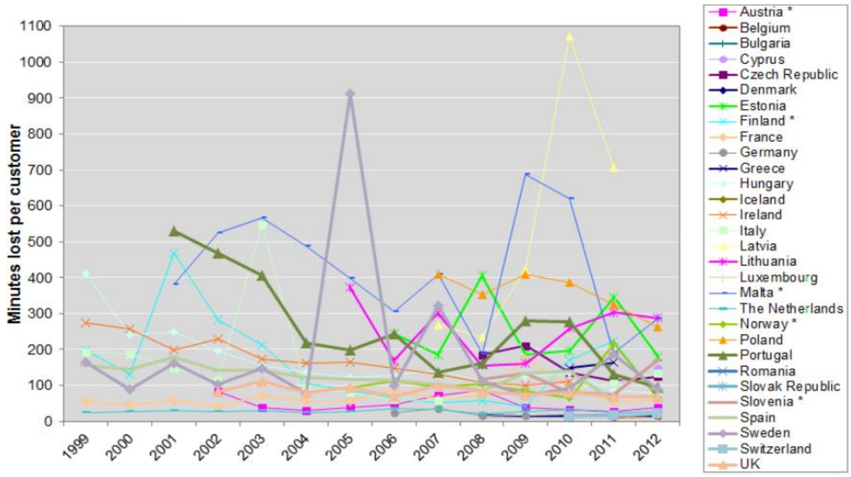
Table 1 - Comparison of outage cost studies for residential consumers (VoLL)

Reference	Country	VoLL (€/kWh)
Baarsma and Hop (2009)[9]	Netherlands	3.66
Bertazzi, Fumagalli et al. (2005)[10]	Italy	10.89
Bliem (2008)[11]	Austria	5.3
Kjølle, Samdal et al. (2008)[12]	Norway	1.08
Lawton, Sullivan et al. (2003)[13]	USA	7.8

The VoLL for different countries vary due to factors such as the method used to value lost leisure time (e.g. non-paid time, during weekends) and the time or season of occurrence. In developed countries with more severe winters, the total electricity consumed on a winter evening may be relatively high. Since the electricity consumed is in the denominator of calculating the VoLL, a higher electricity consumption may result in a lower VoLL (although

[2] Tishler, Asher, "Optimal production with uncertain interruptions in the supply of electricity: estimation of electricity outage costs". European Economic Review 37, 1993, p. 1259 – 1274.
[3] Billinton, R., Tollefson, G., Wacker, G., "Assessment of electric service reliability worth". Electrical Power & Energy Systems 15 (2), 1993, p. 95 – 100.
[4] Ajodhia, V., van Gemert, M., Hakvoort, R., "Electricity outage cost valuation: a survey". Discussion paper, DTe, Den Haag, the Netherlands, 2002
[5] Day, W.R., Reese, A.B., "Service Interruptions: The Customers' Views", Pacific Gas & Electric Company, USA, 1992
[6] Beenstock, Michael, Ephraim, Goldin, Yoel, Haitovsky, "Response bias in a conjoint analysis of power outages". Energy Economics 20, 1998, p. 135 – 156.
[7] Elforsk,"Does it Matter When a Power Outage Occurs - A Choice Experiment Study on the Willingness to Pay to Avoid Power Outages", May 2005
[8] Johannes Reichl, Michael Schmidthaler, Friedrich Schneider, "The Value of Supply Security: the Costs of Power Outages to Austrian Households, Firms and the Public Sector", Energy Economics 36, 2012, p. 256–261.
[9] Baarsma, B.E., Hop, J.P.,"Pricing power outages in the Netherlands". Energy 34 (9), p. 1378–1386, 2009
[10] Bertazzi, A., Fumagalli, E., et al., "The use of customer outage cost surveys in policy decision-making: The Italian experience in regulating quality of electricity supply". CIRED, 2005
[11] Bliem, M., "Ökonomische Bewertung der Versorgungsqualität im österreichischen Stromnetz und Entwicklung eines Modells für ein Qualitäts-Anreizsystem". Klagenfurt, Alpen-Adria-Universität Klagenfurt, 2008
[12] Kjølle, G.H., Samdal, K., et al. "Customer costs related to interruptions and voltage problems: Methodology and results", IEEE Transactions on Power Systems 23 (3), p. 1030-1038, 2008
[13] Lawton, L., Sullivan, M., et al., "A Framework and Review of Customer Outage Costs: Integration and Analysis of Electric Utility Outage Cost Surveys", B. Lab. Berkeley, Environmental Energy Technologies Division, 2003

Figure 1 - Unplanned interruptions >3 minutes[13]



the price of electricity itself during this period may remain high).

2. <u>Production-function approach:</u>
This approach aims to estimate the welfare costs of a power-supply interruption across different sectors, durations and times of occurrence in a week (weekday during the day, weekday evenings, and weekends) and includes studies based on macro-economic indicators. This can be quantified through lost production for the commercial sector and lost convenience (or leisure time) for households. Within the production-function approach, quantitative statistical information is used to determine the costs in relation to a given supply interruption[14]. The lost production in each sector during an outage can be estimated directly and then aggregated to a macro-economic total. Interactions between sectors can also be evaluated through input – output tables[15].

3. <u>Market behaviour (revealed preferences):</u> Another method to estimate how the industrial, commercial and households sectors value supply interruptions is through information on their expenditures on backup facilities, interruptible contracts and interruption insurances. The level of expenditure on backup facilities indicates how much businesses, industry and households are willing to pay for a higher level of supply security[16]. Past studies advocating this method were applied to cases with an average of 10 hours of interruptions per year[17]. For most of the EU, this value is larger than the cumulative duration of interruptions in a year (see **Figure 1[18]**). In an EU context, backup generators would only have to be used for short periods of time. This would mean that the cost of capital per minute of operation is often too high for businesses or households to invest in backup technology (exceptions include hospitals and banks). This is in contrast to the US, where 22% of the peak demand equalling 170 GW is available in the form of consumer backup generators. This includes generators of up to 60 MW, but 98% of them are smaller than 100 kW[19]. In the case of Europe, the market for diesel generators has shown signs of steady growth in the past few years[20]. However, a figure of total backup generator capacity currently present in the EU could not be identified.

4. <u>Case studies:</u> There are two main approaches to using case studies to estimate the cost of supply interruptions. In one method, effects of an actual supply interruption are first listed and these are then monetized[21]. Another approach is to undertake direct

[14] Munasinghe, M., Gellerson, M., "Economic criteria for optimizing power system reliability levels". The Bell Economic Journal 10 (1), 1979, p. 353 – 365.
[15] Chen, Chiung-Yao, Vella, Alfred, "Estimating the economic costs of electricity shortages using input – output analysis: the case of Taiwan". Applied Economics 26, 1994, p. 1061 – 1069.
[16] Caves, Douglas W., Herriges, Joseph A., Windle, Robert J., "The cost of electric power interruptions in the industrial sector: estimates derived from interruptible service programs". Land Economics 68 (1), 1992, p. 49 – 61.
[17] Sanghvi, A.P., "Economic costs of electricity supply interruptions: US and foreign experience". Energy Economics 4 (3), 1982, 180 – 198.
[18] "CEER Benchmarking Report 5.1 on the Continuity of Electricity Supply", February 2014
[19] "Backup Generators (BUGS): The Next Smart Grid Peak Resource", National Energy Technology Laboratory, 2010.
[20] Deubel, Karsten, "Central and Eastern European Diesel Generator Set Market". Frost & Sullivan, 2013
[21] Corwin, J., Miles, W., "Impact Assessment of the 1977 New York City Blackout". US Department of Energy, Washington, DC. July, 1978

surveys after an interruption[22]. An advantage of case studies is that an actual rather than a hypothetical interruption is studied. Also, the interruption studied can be representative of other interruptions in similar circumstances (geographical location, time of occurrence and duration of interruption), and may be used to draw some general conclusions. Some studies have shown that revealed preferences (market behaviour) provides a more objective basis than subjective valuation (surveys) for estimating the cost of power outages, as it reflects "what people do rather than what they say". In the following sections, selected case studies are presented to highlight differences between supply interruptions based on factors such as geographical location, associated level of grid interconnections, duration, and time of occurrence.

Isolated and vulnerable: Case study of Cyprus (2011)

As an island state and due to the absence of any interconnections, the grid network of Cyprus is currently isolated. Therefore, vulnerability due to sudden variations in generation from variable renewables or due to outages is quite high. One such occurrence of great magnitude occurred on 11th July 2011, when 98 containers of ammunitions and other material exploded at a naval base in close proximity to the biggest power plant of the island. The Vasilikos facility, which was severely damaged as a result, had an installed capacity of 648 MW and corresponded to 53% of the generating capacity of the Electricity Authority of Cyprus (EAC)[23], the sole utility on the island.

Since this incident took place during a high demand season, rolling blackouts subsequently followed, affecting the ability of commercial services and industry to operate. At the time, there was a decision to protect hospitals, police stations, the tourism sector and large industrial users from these blackouts[24]. In order for the island to address the major loss in generating infrastructure, the Israeli Government provided 15 MW of standby generators, the Greek Government supplied temporary generating units of 71.6 MW and 120 MW were secured from a power company operating in Northern Cyprus (until February 2012). During the summer of 2012 an additional 120 MW of temporary generating units were installed in order to meet the high power demand of the season.

As a consequence of the use of less cost-efficient generation options to cover electricity demand, Eurostat reports an electricity price increase of 36% for average households between the first half of 2011 and 2012 and an increase of 26% for industrial consumers[25] (**Table 2**). Additionally, the restoration of the Vasilikos facility was estimated at a cost of €220 million[26] and was completed during 2013[27].

Table 2 – Electricity prices for medium sized households[28] and industry[29,30] (€/kWh)

Households			Industry		
2011 Q 1-2	2011 Q 3-4	2012 Q 1-2	2011 Q 1-2	2011 Q 3-4	2012 Q 1-2
0.205	0.241	0.278	0.167	0.211	0.211

The case of Cyprus is particularly interesting within the context of long-term interruptions in electricity supply. In a situation of an island lacking interconnection with other grid networks, ensuring uninterruptible supply of energy services is critical and requires careful planning. Extreme events such as the one experienced in Vasilikos are very challenging to manage and political decisions are required to prioritize which customers should be protected and which services should remain unaffected.

Timing matters: Case study of Italy (2003)

One of the most reported and researched power outages in recent years occurred in Italy on 28th September 2003. At about 3 a.m., power coming from Switzerland to Italy was cut off as two key transmission lines across the border were damaged in a storm. As a result, all of Italy – except the islands of Sardinia and Elba – remained without

[22] Serra, Pablo, Fierro, Gabriel, "Outage cost in Chilean industry". Energy Economics 19, p. 417 – 434, 1997
[23] EAC, "Annual Report 2012," Electricity Authority of Cyprus, 2013.
[24] S. Orphanides and P. Tugwell, "Cyprus Blast Kills 12, Injures 62, Reduces Power by 50%," Bloomberg, 11-Jul-2011. [Online]. Available: http://www.bloomberg.com/news/2011-07-11/cyprus-fire-that-killed-eight-spread-from-power-station-to-munitions-store.html. [Accessed: 10-Oct-2014].
[25] Eurostat, "Electricity and natural gas prices: 2012 semester 1," European Commission, 2013.
[26] EAC, "Annual Report 2011," Electricity Authority of Cyprus, 2012.
[27] EAC, "Annual Report 2012," Electricity Authority of Cyprus, 2013.
[28] 2 500 kWh < Consumption < 5 000 kWh
[29] 500 MWh < Consumption < 2 000 MWh
[30] Eurostat, "Electricity and natural gas prices: 2012 semester 1," European Commission, 2013.

power for up to 12 hours. Affecting a total of 56 million people, it was the largest blackout in Italy in 70 years. In the immediate aftermath of the blackout, 110 trains were cancelled, with 30,000 people stranded on trains across Italy.

The root causes of the failure of the transmission line and the subsequent power outage have been extensively studied[31,32,33,34]. The case of the power outage in Italy is of special significance as it underscores the importance of considering the time of occurrence while estimating the costs of interruption.

The night of 27 September, 2003 was the annual overnight festivities, Nuit Blanche (White Night) in Rome. As a result, many people were on the streets and all public transportation were still operating around the time of the blackout, despite the fact that it was very late at night. Several hundred people were trapped in underground trains. Coupled with heavy rain at the time, many people spent the night sleeping in train stations and on streets in Rome. While it was reported that emergency services coped well with the situation, several traffic accidents were said to have been caused as a result of the failure of traffic signals[35].

In recent years, only a limited number of studies took into consideration the specific circumstances of the time of occurrence of interruptions[36]. Yet, information on the services interrupted and their correlation to the time of occurrence can be used to operate the power system more effectively from a societal perspective. For instance electricity producers, Transmission System Operators (TSOs) and local network operators can make decisions about maintenance that influence the probability of a supply interruption.

Case studies such as those presented on Cyprus and Italy provide important insights to understanding the implications of outages in existing power systems. The situation may however change as power systems accommodate higher shares of variable renewable energy sources.

Integrating renewables through smarter grids: trade-offs and synergies

Ensuring a cleaner supply of energy drawing on locally available renewable energy resources has become a key policy objective of European governments. The growing reliance on renewable power sources may result in significant instantaneous shares of their generation. Balancing their often variable output requires a high degree of flexibility in the power system, i.e., changes in generation or demand must be counterbalanced quickly enough to avoid supply interruptions.

<u>Distributed renewables and storage:</u> When solely looking at the level of interruptions, a system with and without renewables may be designed to be the same from a reliability perspective. Yet, from an operational point of view this is commonly not the case. Renewable generation often involves distributed generation by households or municipalities. For example, some small hydro power plants which were built in response to Austria's feed-in-tariffs are capable of black-start and isolated operation. As such, the local municipality may still be supplied with electricity even if a major outage in the transmission system occurs. (Note that such decisions taken by local municipalities were rather political than technical, to avoid complaints by their respective constituencies in case of outages.)

Similarly, household PV and solar thermal systems may also provide energy services when outages occur. Germany, for example, launched a support programme for PV storage systems, providing a mix of low-interest loans and subsidies for up to a maximum of 30% of the investment cost[37]. The

[31] UCTE (Union for the Coordination of Electricity Transmission), "Final report of the Investigation Committee on the 28 September 2003 Blackout in Italy", April 2004
[32] Sergey V. Buldyrev, Roni Parshani, Gerald Paul, H. Eugene Stanley & Shlomo Havlin "Catastrophic cascade of failures in interdependent networks", Nature Letters, Vol 464, 2010
[33] SFOE (Swiss Federal Office of Energy), "Report on the blackout in Italy on 28 September 2003", November 2003
[34] Chris. W. Johnson, "Analysing the Causes of the Italian and Swiss Blackout, 28th September 2003", Proceedings of the twelfth Australian workshop on Safety critical systems and software and safety-related programmable systems, Volume 86, 2007, p. 21-30
[35] "Huge blackout cripples Italy", BBC, 28 September, 2003, [Online]. Available: http://news.bbc.co.uk/2/hi/3146136.stm [Accessed: 10-Oct-2014]
[36] Michiel de Nooij, Carl Koopmans, Carlijn Bijvoet, "The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks". Energy Economics 29, 2007, p. 277 – 295.
[37] Wolfram Schweickhardt, "KfW and Federal Environment Ministry Launch Programme to Promote Use of Energy Storage in Solar PV Installations," KfW, 2013, [Available

advantages to society are twofold. The system would increase the supply security of the connected households in the case of outages. Further, the system reduces the pressure on local grids by reducing the peak production of the PV systems.

Decentralised generation has a clear potential to reduce the costs of intermittency by reducing the number of consumers affected, e.g., by an outage in a main transmission line. However, the distribution of the costs for accessing the grid do require consideration. If added as a surcharge to the electricity consumption, such households or municipalities may not pay their fair share due to their low consumption. The share of the grid costs per capacity connected and per electricity generated may need to be revisited to ensure costs and benefits are adequately attributed to the various consumer groups.

Unlike distributed storage options, larger wind farms are commonly built in a more concentrated fashion in areas with favourable wind conditions. Similar to large hydro power plants, they require medium to large voltage grid connections to be established. Depending on the size of the power plant, an outage in such a line may therefore have an effect similar to an outage in a connection to a thermal power plant.

Smart Grids: Increasing shares of renewables (distributed) call for a more flexible power system controlled through smarter grid management techniques. Smart Grids build on a significant increase in the level of communication, automation and control based on a two-way flow of information and electricity, from supplier to consumer.

One characteristic of Smart Grids is their ability to be self-healing, i.e., to reduce the extent of interruptions and restore the system's operation when outages do occur. Smart Grids further enable the integration of sources of flexibility which were largely untouched before. This is especially important as increasing the share of variable electricity generation will require a more flexible system based on parallel investments in balancing mechanisms. Conventionally, this would be provided by power plants which can quickly ramp up or down their generation, such as gas turbines. With the advent of Smart Grids, more accessible and cost-efficient options will be available to minimise the extent and costs of interruptions to customers.

Demand-side management and prioritisation of loads: Smart Grids may minimise the cost of interruptions by ensuring near perfect reliability and quality of supply for high priority demand types, while reducing the requirements for demand types which are less sensitive to these needs[38]. Loads may be prioritised according to demand types such as emergency services, financial institutions, industries, and consumers.

Such a prioritisation may not be limited to consumer groups, but may also apply to demand types within one consumer group. For example, approximately half of private household demand does not need to be met instantly and can be shifted flexibly[39]. Examples include dishwashing, washing of clothes, air conditioning and heating. In the transport sector, electric vehicles may provide this flexibility. In industry, related examples include electric boilers or process heat requirements. So instead of having to cut off several consumer groups completely, with Smart Grids specific demands may be interrupted, thus ensuring the supply to more high-value energy services and reducing the cost of interruption. An example of a deconstructed demand profile based on different priorities and flexibilities is provided in **Figure 2**[40].

According to ACER's estimates, currently only 10%of demand response resources is being utilised within the EU. Pricing schemes would need to ensure that the flexibility provided by consumers is rewarded accordingly. Supportive regulation is needed, not least to ensure cyber security and protect consumers from data misuse.

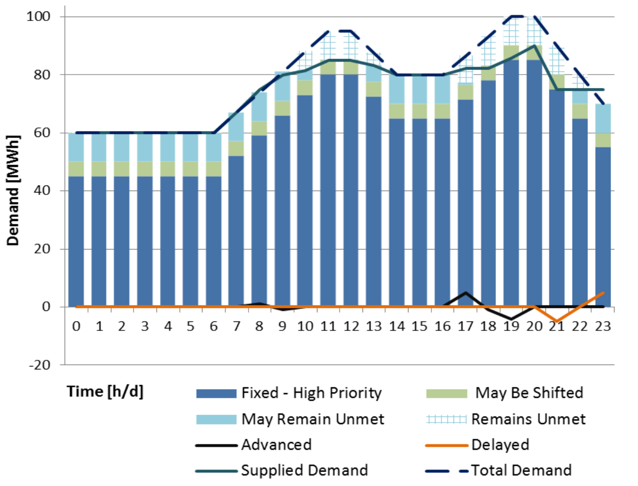
online: https://www.kfw.de/KfW-Group/Newsroom/Aktuelles/Pressemitteilungen/Pressemitteilungen-Details_107136.html. Accessed on: 15 October 2014]

[38] "Energy Technology Perspectives 2010: Scenarios and Strategies to 2050", International Energy Agency, 2010

[39] C. Block, D. Neumann, and C. Weinhardt, "A Market Mechanism for Energy Allocation in Micro-Chp Grids" in Proceedings of the 41st Hawaii International Conference on System Sciences, 2008, 172–180.

[40] M. Welsch et al., "Modelling Elements of Smart Grids – Enhancing the OSeMOSYS (Open Source Energy Modelling System) code", Energy 46 (1), 2012, p. 337–350

Figure 2 – Supply analysis to meet demand types with different prioritisations and flexibilities



Regulation: Present regulation often rewards utilities for delivering network primary assets rather than improving performance through more sophisticated grid management and consumer integration. Thus, regulation can hinder developments that do not focus on investments in network assets. Most current network design and operation practices centre on variations of the historic deterministic N-1 approach that were developed in the late 1950s. A system which adheres to the N-1 rule maintains reliable operation even if a major element fails, e.g., a transmission line. This approach has broadly helped deliver secure and reliable electricity services, alongside various other traditionally applied redundancy measures. It can, however, impose major barriers for innovation in network operation and for the implementation of solutions that enhance the utilisation of grid assets. Moving away from such historically developed power quality and reliability standards will help balancing asset- and performance-based options, particularly those that involve responsive demand and advanced network management techniques facilitated through Smart Grids.

According to a recent study on demand response measures[41], few of the EU 28 Member States were found to have created satisfactory regulatory and contractual structures that support aggregated demand response resources (**Figure 3**). Some Member States are in the stage of reviewing their regulatory framework (such as Austria, UK, Ireland, Germany and France), while most Member States are lagging in regulatory and institutional terms that hinder consumer participation in balancing, reserves, system services and energy markets.

Figure 3 - Overview of progress of European countries relevant to deployment of demand response

Increasing generation from variable renewables requires an increase in power system flexibility to ensure current reliability standards are met. The increased flexibility requirements may trigger investment in a set of smart technologies, which may ultimately allow decreasing the costs of intermittency. This may be achieved by shifting the current focus on the provision of electricity to a focus on the provision of services.

Services, not kWh: Expanding the approach

Previously we have highlighted the need to differentiate between various consumer groups. Going one step further, it may be useful to differentiate between the values of specific energy services in order to assess the socio-economic implications of interruptions.

[41] Smart Energy Demand Coalition, "Mapping Demand Response in Europe Today", April 2014

From the point of view of the economy, almost no activity or production can take place without an 'energy service'. Activities and products command different market values. Thus, energy-services have different values. For example, for a European household heating a home might be more valuable than keeping the television on. Similarly, the energy-service of keeping a company's servers running might be more valuable than the energy service of cooling drinks for the company's employees. If there is a power cut there would be much greater damage incurred if the servers are affected than the vending machine. Yet, unless some local backup power is available, there is no differentiation between these different values for services during a power cut. That results in blanket cuts across all services, valuable or not, when there is an interruption.

To limit damage, it would require a shift to manage electricity use at the level of services rather than by consumer or 'consumer group'. Herein there are strong synergies with Smart Grid developments, where the use of electricity by devices can increasingly be remotely controlled. If interruptions can be limited to lower value uses of electricity their damage might be powerfully limited. This could be facilitated by (1) incentive programmes to encourage network operators to support a more active role of consumer engagement and by (2) enforcing automatic individual customer compensations for power supply interruptions according to the occurred damage.

Looking forward

In order to calculate economically optimal interruption levels, knowing the value that society places on it is an important first step. A first step could be to replace reliability standards that in most Member States are still based on past engineering practice and rules of thumb with a more technology neutral and market based approach. This could be achieved by comparing the damage to society with the costs of new investments to increase the systems reliability. This would require putting a price tag on interrupting various forms of energy services, based on the duration of the interruptions and the consumers' willingness to pay. One may argue that even an initial estimate is better and allows for a more market based approach than not having any such value. The alternative, e.g., to define an LOLP and design the system accordingly, may be more arbitrary. While better information may be available for industries, the estimations of the willingness to pay can be improved as further information becomes available, e.g., from smart home systems.

Once these values are defined, modified versions of outage simulation tools such as APOSTEL and energy and power system models such as OSeMOSYS, MESSAGE, TIMES or PLEXOS may be applied to optimise the extent of interruptions and minimise the costs for society[42]. The model might be set up to investigate to what extent increased variability in generation needs to be balanced and how to best do so, e.g., by investments in hydro storage, electric vehicles, or demand-side measures. Overall, the model may choose among all competing options and, assuming 'perfect competition' between all technologies, will invest only in those which are most economically efficient. This information will be valuable for both, to inform the development of energy strategies and for TSOs, who are in charge of ensuring a reliable supply.

To enable the balancing of increased reliability with the costs associated with achieving this reliability, we propose to develop a detailed analysis of the cost of outages for each EU Member State. This will enhance and build on existing efforts to include parameters such as services interrupted, geographical location, and time of occurrence and duration of interruptions. The development of a standardised database for aggregating costs of interruption could then serve to better integrate them in power system planning and operation. This could be achieve, for example, by combining a production-function approach based on WTP assessments with energy system planning tools that consider a closer consumer integration through Smart Grids. A follow up report to this brief could demonstrate the value of such an approach by focusing on individual EU Member States with good data availability. The insights gained may be valuable to help markets to more optimally price and combine reliability services provided by the grid infrastructure, power generation options and consumers.

[42] M. Welsch et al., "Incorporating Flexibility Requirements into Long-Term Models – A Case Study on High Levels of Renewable Electricity Penetration in Ireland", Applied Energy, 2014, doi:10.1016/j.apenergy.2014.08.072.

Afterword: Outside the EU

The US continues to grapple with power outages, with reports estimating a 285% increase in the number of outages since 1984[43]. Weather events are the single largest cause for outages, being responsible for 87% of all outages affecting over 50,000 people. Estimates of the yearly costs of outages range between $28-209 billion[44]. Two thirds of the related costs are expected to be caused by interruptions lasting less than five minutes due to their high frequency. Some estimates suggest that Smart Grids could help reduce the cost of outages in the US by up to $49 billion per year[45]. The situation is much worse in less developed countries such as India, which faces power outages of up to an estimated 30,000 MW (12% of total installed capacity) during summer months[46]. Highlighted by the massive blackout of 2012 that left 620 million people without power, India's power crisis has widespread effects on both social and economic development.

Table 3 shows the current situation in Sub-Saharan Africa, in contrast to the global average. In particular, it shows that electricity interruptions affect businesses the most, with most firms requiring a generator to provide a third or more of their electricity.

In comparison to the situation in other developed and developing countries, the EU can set the global benchmark for minimising the socio-economic costs of supply interruptions.

Table 3 – Power outages in Sub-Saharan Africa

Indicator	Senegal	Nigeria	Sub-Saharan Africa	World
Number of electrical outages in a typical month	25.8	26.3	10.7	8.6
Duration of a typical electrical outage (hours)	2.3	8.2	6.6	4.0
Losses due to electrical outages (% of annual sales)	5.1	8.9	6.7	4.8
Percent of firms owning or sharing a generator	90.7	85.7	43.6	31.6
Proportion of electricity from a generator (%)	30.8	47.5	13.8	7.1
Percent of firms identifying electricity as a major constraint	57.5	75.9	50.3	39.2

For further reading or information, please visit www.insightenergy.org

[43] Meagan Clark, "Aging US Power Grid Blacks Out More Than Any Other Developed Nation", International Business Times, July 2014. [Available online: http://www.ibtimes.com/aging-us-power-grid-blacks-out-more-any-other-developed-nation-1631086. Accessed on: 17 October, 2014]
[44] Costs calculated through surveys, national statistics and cost functions. For further detail refer to Executive Office of the President, „Economic Benefits of increasing electric grid resilience to weather outages", 2013.
[45] Massoud Amin, "We need stronger, smarter electrical grids", July 2014. Ensia [Available online: http://ensia.com/voices/we-need-stronger-smarter-electrical-grids/. Accessed on: 17 October, 2014]
[46] Utpal Bhaskar,"India faces daily power outage of 30000 MW", Live Mint, [Available online: http://www.livemint.com/Industry/tnV2NUSAK8PbFs7pSzoL0I/India-faces-daily-power-outage-of-30000-MW.html. Accessed on: 17 October, 2014]