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# Valuing blackouts and lost leisure: Estimating electricity interruption costs for households across the European Union

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## ABSTRACT

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. Several previous studies estimate the cost of electricity interruptions for individual European Union (EU) Member States – as the Value of Lost Load (VoLL). In this paper, we use a production-function approach to estimate the average annual VoLL for households in all twenty-eight EU Member States. This is the first time that a unified approach has been applied for a single year across the EU. VoLL is further presented on an hourly basis to better understand the impact of the time at which the interruption occurs. Finally, we analyse the impact of 'substitutability factor' – the proportion of household activities that are electricity-dependent – on the VoLL. Results from this study show that the differences in VoLL between EU Member States is significantly large, ranging from 3.2 €/kWh in Bulgaria to 15.8 €/kWh in the Netherlands. The annual average VoLL for the EU was calculated to be 8.7 €/kWh. Results from this study can be used to inform key areas of European energy policy and market design.

## 1. Introduction

Reliable and affordable electricity supply is critical for any economy to function efficiently. While Europe has enjoyed a high degree of supply security during the last few decades, the utility industry has identified 'liberalization and privatization' (which largely took place in the 1990s) and 'renewable capacity expansion' (which forms an essential option for sustainable energy systems) as the two major trends that increase the risk of power outages [1,2]. Increased shares of renewable energy sources (RES) affects energy security in several ways. From a long-term perspective, increased shares of RE positively affect energy security due to decreased reliance on depletable, and often imported, fossil fuels. In the short-term, however, the variability and temporal mismatch between demand and supply poses a considerable challenge to the integration of RES [3,4]. The EU, which pursues a policy of increasing the share of RES in national and regional generation mixes, must make additional efforts in order to maintain current levels of supply reliability. These may include grid adaptations as in the case of Germany [5] or Performance-Based Regulation (PBR) for Distribution System Operators (DSOs) in the UK [6]. As part of its Trans-European Energy Network planning, the European Commission foresee the application of a neutral pan-European transmission cost–benefit analysis (CBA) to facilitate the optimal expansion of the electricity transmission system [7]. Such a strategy would require information on the monetary value of supply of security in order to arrive at an 'optimal' solution from both a technical and a socio-economic perspective.

End-users in an electricity system expect a reliable supply, available on demand. RES intermittency is already significantly changing the design of electricity markets, where it is leading to a paradoxical situation: back-up capacity is needed for a secure electricity supply but the right market incentives to ensure such capacity is absent [8]. Flexibility is also needed in the power system to respond to the increasingly sharp short-term variations in the market. Most grid expansion options involve significant investment expenditures, which must be justified by the potential adverse impact of compromising power supply security. Since nearly every economically productive activity is dependent on a reliable supply of electricity, power outages can have potentially far-reaching consequences for the entire socio-economic system. This study aims to provide information that can be useful to determine financial incentives to improve electricity supply

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reliability.

Currently, reliability levels are often 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 [9,10]. Other design criteria are redundancy measures to ensure the system can cope with an outage in essential supply infrastructure (e.g., N-1 rule) [11,12]. 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 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 study provides guidance on how to value the consequences of supply interruptions and thus determine the demand for security of electricity supply.

From a socio-economic perspective, the most commonly used indicator to measure interruption costs is the value of lost load (VoLL[1]). VoLL is likely to play a significant part in informing a number of key areas of European energy policy and market design. In Capacity Markets, for instance, the amount of electricity generating capacity required in each EU Member State (MS) and that will be contracted through a Capacity Market is likely to be informed by the VoLL. For balancing markets, VoLL can represent the cost of electricity interruptions to end-users [13,14]. VoLL will therefore be used in a range of policy and market design decisions at both the EU level and Member State levels.

Further, the household sector is often overlooked in discussions of supply security. However, the welfare losses of households (lost leisure) can be as important as the lost value addition of firms. Studies such as de Nooij et al. [15], in a study of the Netherlands, find that on a weekday in the evening the cost of a supply interruption is largest for households. Households, however, do not receive adequate attention in decisions on supply security. It is interesting to note that the number of publications on estimating VoLL has increased in recent years. Schröder and Kuckshinrichs [2] report that Germany has published six studies on the topic, all of them after 2011. As mentioned earlier, the increased penetration of RES – as is the case in Germany – is a strong justification to estimate the costs of electricity supply interruptions.

At present, VoLL is completely lacking in international comparability. A uniform analytical framework is therefore urgently required [2]. In this paper, VoLL for households in all twenty-eight EU Member States is estimated based on a uniform methodology for the first time. The findings are envisaged to provide a basis for meaningful comparison between EU Member States. We use an established methodology, previously employed by several studies to estimate VoLL for households at the national level [16,17,19,20]. As the EU moves towards a common internal energy market, it is increasingly important to align the economic incentives of different EU Member States in ensuring reliable electricity supplies, both within and between Member States. Further, we study the time-varying nature of VoLL to identify both the time and location of highest potential electricity interruption costs for households. Finally, we analyse the impact of 'substitutability factor' – the fraction of leisure activities that are electricity-based – on the VoLL. This is also the first attempt to perform such a sensitivity analysis on VoLL for households.

The rest of this study is structured as follows. Section 2 presents a literature review with common methods used to quantify electricity outage costs and compares the results obtained from studies using these different methods. Section 3 describes the methodology adopted in this study known as the production-function approach. In Section 4, the results obtained for all EU Member States is presented. Section 4.1 compares VoLL values between Member States on an annual average basis, while Section 4.2 presents VoLL on an hourly basis to demonstrate the time-varying nature of outage costs. In Section 4.3, a sensitivity analysis of the influence of 'substitutability factor' on VoLL is discussed. Section 5 concludes with a discussion of the main outcomes of the study. Further, it provides policy recommendations and suggestions for future research.

## 2. Literature review

Commonly used technical indicators of power system reliability include SAIFI, SAIDI, and CAIDI,[2] which are statistical measures [19]. They are related to average power interruption frequency, duration, and intensity respectively. However, from a socio-economic perspective, VoLL is an important indicator that addresses the impact of electricity supply interruptions and the monetary valuation of a reliable, uninterrupted power supply. VoLL can, therefore, be understood as an economic indicator for electricity security. It is determined by relating the monetary damage arising from an electricity supply interruption – due to the loss of socio-economic activity – to the level of kWh that were not supplied during the interruption [20]. While a representation in monetary units/kWh is most commonly used, VoLL may also be measured in relation to time [21]. We have selected VoLL as an economic indicator of outage costs in this paper since it has a long-established history of usage in the field of power supply security [2,18,22,25,27,28]. Further, it is a more appropriate indicator from a socio-economic perspective as compared to the technical indices mentioned above [2].

Prior to estimating the costs of interruptions, however, it is useful to note that the consequences of supply interruptions are not created equal. 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 [6–13]. Another important aspect is the time of occurrence of the interruption [28]. The type of activity that is interrupted is dependent on the time of day, week and season. For instance, in the case of a household, an interruption at 20:00 may interfere with recreation (e.g. television, internet), while at 3:00 in the morning 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.

It is important to distinguish the impacts of planned and unplanned outages as well. Advance notification of an impending electricity interruption also helps in mitigating its negative implications [15]. For example, if one is made aware of an imminent electricity interruption, then one 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') [29].

Since no market currently exists to trade electricity interruptions, it is not possible to ascertain a "market price" that shows the marginal cost per unit of time of a supply interruption. In this study, we use VoLL as the metric to measure outage costs. VoLL can be considered to be either marginal or semi-marginal, since it depends on the 'discrete size' of demand (in kWh or MWh) not served. For instance, if only a single

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[1] Other terms that are used synonymously with VoLL include "electricity outage costs", "cost of unserved energy", or "customer service reliability".

[2] SAIFI: System Average Interruption Frequency Index; SAIDI: System Average Interruption Duration Index; CAIDI: Customer Average Interruption Duration Index.