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by

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On the Heterogeneity of the Economic Value of Electricity Distribution Networks: an Application to Germany*

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Abstract

The reliability of the electricity grid is of vital significance for the proper functioning of a society and its economy. The aim of this study is to develop a methodology to quantify differences in the electricity distribution grid's economic importance, and investigate limitations from its application to Germany. To this end, the economic value created from electricity consumption is related to the infrastructure installed to generate that economic value. Based on the Value of Lost Load concept, which captures a consumer's willingness to pay for avoided electricity outages, a macroeconomic approach is applied to determine the economic value generated per kWh on the spatial resolution of counties. Each voltage level's grid length is selected as a proxy for the infrastructure installed. Geographic intersections between counties and network operators are exploited to harmonise these data such that both relate to the same reference unit. The results highlight electricity distribution grids of distinct relative economic importance. Especially under consideration of relevant climate risks, the outcomes strengthen the scientific basis for climate services to the energy sector, and can contribute to the design planning of the distribution grid with respect to for example resilience, redundancy, maintenance and retrofitting measures.

Keywords: Blackout costs, Climate Risks, Economic assessment, Electricity distribution networks, Energy transition, Supply Security, Value of lost grid, Value of lost load
JEL classification: D61, L94, Q40, Q41, Q54

1 Introduction

Currently, the German electricity distribution grid is in the process of being significantly altered to respond to challenges linked to the energy transition (Energiewende): Large power generation units feeding into the higher voltage levels of the electricity grid are increasingly replaced by smaller

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units of renewable energies directly feeding into the lower voltage levels. Hence, instead of the hitherto mostly unidirectional power flow from the higher to the lower voltage levels, increasingly often a bidirectional flow occurs (Dondi et al., 2002). In addition, the electricity market gradually develops from a pattern where generation responds to the timing of electricity consumption towards a pattern determined by the availability of renewable electricity (Bayod-Rújula, 2009). Depending on the underlying energy-economic scenario considered, these developments initiate substantial investments into the electricity distribution grid which requires a projected 130,000 to 280,000 km of grid extensions[1] until 2030 or 2032 respectively (Agricola et al., 2012; Büchner et al., 2014).

Besides these considerable investment requirements to adapt the electricity networks to the beforehand mentioned developments, further adaptation may be required to account for changing climatic conditions that alter the probability of events with the potential to trigger electricity outages (see Kovats et al. (2014) for information on a European scale, and Koch et al. (2016) for information on the scale of Germany). With regard to climate change, the electricity transmission and distribution sector has been identified of being vulnerable to altered storm conditions and increases in air temperature (European Commission, 2013; Rademaekers et al., 2011). Historically, in Europe, the majority of customer disconnections occurred in the distribution networks and were related to storms that caused trees or other debris to damage the distribution infrastructure (Ward, 2013). Already today, historic climatic conditions are considered in the grid design: Based on observations on wind and ice conditions, climatic conditions are for example reflected in norms that regulate the resistance of the grid with respect to the local climatic conditions (compare e.g. Deutsches Institut für Normung, 2005).

In order to account for grid extension requirements and altering climatic conditions in the economically most efficient way, the economic value which is at stake has to be quantified. Determining the differences in the economic value of the grid supports assessments, whether the grid design mirrors the actual economic consequences an interruption of the grid would cause. Already in the current grid design, variations in the resilience and redundancy of the grid towards outage events are very common: Lower voltage levels for example, in general have a lesser degree of redundancy than higher voltage levels (Ward, 2013) and, therefore, have better capacities to cope with an outage of any component within the power system. This reflects economic reasoning, since most probably more economic value generation would be affected by an interruption in the higher voltage levels of the grid than in any of the lower levels. In line with this argument, infrastructure resilience and/or redundancy should be designed and maintained based on the economic benefits generated by the respective infrastructures, to avoid grid units of too high or too low network quality (Welle and Zwaan, 2007).

Based on the previous considerations, the central aims of this study is to develop a methodology to quantify differences in the electricity distribution grid's economic importance, to investigate limitations of such a methodology and test its applicability to Germany. The *Value of Lost Load* (VoLL) concept, which measures a consumer's willingness to pay for avoided electricity outages, has been proposed as one guiding variable to determine optimal economic levels of supply security (Welle and Zwaan, 2007). However, a quantitative analysis of the relative economic value of a grid requires information not only on the economic value generated by a unit of delivered electricity, but also on the amount of electricity consumed and the total infrastructure needed to generate the respective economic value. To our best knowledge, there is no methodology yet to combine the latter information, as a variable as a measure to guide network quality considerations. By proposing a concept named *Value of Lost Grid* (VoLG), this paper closes this methodological gap and, thus, provides the basis for assessing the climate change induced economic risks on the electricity distribution networks, and strengthens the scientific basis for climate services (as outlined in European Commission, 2015) to the electricity distribution sector.

[1] Compared to 1.7 million km of total distribution grid length.

As indicated, the VoLG requires information on the VoLL, of which various approaches have been suggested; these can be grouped into direct and indirect methods (Schröder and Kuckshinrichs, 2015). Direct approaches are for example survey studies that inquire how much people would be willing to pay for an uninterrupted supply (e.g. Praktiknjo, 2014), or blackout studies which deduce economic losses from past blackout-events[2] (e.g. Schubert et al., 2013). This paper aims at analysing differences in the economic value at highest possible spatial resolution. Since comprehensive data for blackout studies are not available and willingness to pay surveys on a fine spatial resolution would be very costly and time-consuming, the application of any direct method is not applicable. Therefore, we resort to an indirect method, namely the production function approach, which is based on a macroeconomic production function. This approach features two decisive advantages: (i) it relies on easily accessible and mostly cost-free macroeconomic data; (ii) it enables to calculate VoLLs on a relatively high spatial resolution (limited only by the resolution of the collection of macroeconomic data by statistical offices). This approach has been applied to determine VoLLs on different scales of spatial resolution for various countries: Bliem (2005) determined VoLLs on NUTS 2 resolution (federal states) in Austria, de Nooij et al. (2007) and de Nooij et al. (2009) for NUTS 3 level resolution (the so-called COROP regions) in The Netherlands, Tol (2007) and Leahy and Tol (2011) for the combined electricity market of the Republic of Ireland and Northern Ireland, Linares and Rey (2013) for the Spanish NUTS 2 regions, and Zachariadis and Poullikkas (2012) for the electricity market of Cyprus. For Germany, Röpke (2013) determined country-wide VoLLs for five industries plus the households sector, Growitsch et al. (2014) calculated VoLLs for 15 industries and the private sector on NUTS 2 resolution (16 federal states), whereas Piaszeck et al. (2014) and Wolf and Wenzel (2015) further refined the spatial resolution to the around 400 NUTS 3 regions (counties) and four industries plus the household sector.

This paper applies a VoLL estimation on NUTS 3 resolution as conducted by Piaszeck et al. (2014) and Wolf and Wenzel (2015) as a tool to quantify the total economic value annually generated due to the secure functioning of the distribution grid infrastructures. The VoLG calculation requires to combine macroeconomic data and structural grid data[3]. Hence, a harmonisation of the spatial resolution of data sets is conducted, since the two sets do not relate to the same geographic reference domains. Geographic intersections between counties (reference unit of macroeconomic data) and grid operators (reference unit of operators) are exploited to determine the VoLL for the electricity consumed from a certain distribution grid operator's (DGO) voltage level. Accordingly, the total economic value attached to the consumption of the electricity supplied by a specific voltage level is deduced. Thereafter, this economic value is related to the total grid length of that voltage level, to enable comparison between different operators and voltage levels.

Section 2 describes how the economic value of a grid was quantified and related to the infrastructure installed, and refers to the limitations inherent in the applied approaches. Section 3 provides information on the data sources used. In section 4, it is shown that the VoLG may vary significantly between different DGOs by more than an order of magnitude even within one and the same voltage level; the difference in the relative economic importance between the low and the medium voltage level is quantified, and domains whose electricity infrastructure is of comparable higher economic relevance are identified. Further, uncertainties induced by the suggested methodology are quantified. We conclude and discuss the results in section 5.

[2]For a more complete list on direct approaches and recently conducted studies, as well as the advantages and disadvantages of these approaches, we refer to Schröder and Kuckshinrichs (2015).

[3]Such as the total electricity consumption from each voltage level of a certain distribution grid operator.

2 Methodology

In this section, a methodology is developed to quantify the economic value of an electricity distribution grid and relate it to the infrastructure needed to generate that value. To this end, the VoLL is, firstly, calculated on county resolution for five different sectors (subsection 2.1); Subsequently we elaborate on how to derive the VoLL with respect to each distribution grid operator (subsection 2.2); Finally, the Value of Lost Grid concept is proposed as a measure to express a grid infrastructure's relative economic value (subsection 2.3)

2.1 Value of Lost Load on County Resolution

As stated in section 1, there are numerous approaches on determining the VoLL. For the reasons mentioned, an indirect approach based on macroeconomic data, was chosen for this study. In this regard, this study largely follows the methodology as applied by Piaszeck et al. (2014); Wolf and Wenzel (2015), apart from deviations in certain assumptions, and the application of updated data.

In a first step, the VoLL is determined county-wise for each sector. This study differentiates between the four economic sectors *Agriculture*, *Construction*, *Manufacturing & Mining* and *Services*, and the *Household* sector[4]. In line with the literature (e.g. Growitsch et al., 2014; de Nooij et al., 2007, 2009; Leahy and Tol, 2011), the production function approach is chosen, making use of a Leontieff production function, which is characterized by zero substitutability of electricity with any of the other input factors. In other words, a direct linear relationship between production and electricity use is presumed. Based on these thoughts, the VoLL of a sector s in a county c can be determined from the ratio of the gross value added by the respective sector s in the respective county c, $\mathrm{GVA}(s,c)$, and the electricity consumed, $\mathrm{EC}(s,c)$, by the respective sector:

$$\mathrm{VoLL}(s,c) = \frac{\mathrm{GVA}(s,c)}{\mathrm{EC}(s,c)} \tag{1}$$

Production functions are commonly applied to estimate production on the timescale of a year. Hence the capability to precisely estimate outage costs resulting from interruptions of a few hours to days might be limited (Leahy and Tol, 2011). Further, it has been noted that the simplifying assumptions underlying the production function approach may lead to over- as well as underestimations of the real costs of an electricity outage (de Nooij et al., 2009): An overestimation could result from the fact that backup generators, catching-up effects (compensate delayed production through overtime or stock-keeping) and adaptive responses to a blackout are not taken into account (Piaszeck et al., 2014). However, Wolf and Wenzel (2015) argue that for the purposes of cross-regional comparisons this constitutes only a minor problem. An underestimation could be caused by production processes very sensitive to outages, such that a short outage leads to a comparably long interruption until processes can be restarted. The unequal distribution of such sensible sectors across counties may lead to biases reducing the validity of interregional comparisons (Piaszeck et al., 2014). Moreover, the linearity assumption inherent in the Leontieff production function seems reasonable for energy-intensive production processes, whereas it might underestimate substitution options for the construction sector and other labour-intensive services (Piaszeck et al., 2014). However, it has been argued that this does not induce a significant bias, due to the fact that keeping up productivity during an outage requires significant reorganisational efforts and costs (Piaszeck et al., 2014).

For most sectors, the application of Eq. 1 is rather straightforward. However, determining the household sector's VoLL is contingent upon estimations of the value of electricity-dependent leisure activities. This issue was approached applying microeconomic theory, according to which

[4] This differentiation is determined by the aggregation level of data as collected by statistical offices.

total labor supply is determined from each individual maximising its personal utility resulting from work and leisure (Becker, 1965). When each individual can freely allocate its time between work and leisure, the situation can be interpreted as an optimisation problem, which is solved by each individual allocating its time such that marginal benefits from work equal marginal benefits from leisure. Based on the previous considerations and due to a lack of information on marginal wages, average net wages per hour were suggested to be used as a proxy of leisure-induced gross value added (e.g. de Nooij et al., 2007; Growitsch et al., 2014). This approach is sometimes referred to as the *household income approach* (e.g. Schröder and Kuckshinrichs, 2015).

Since not all leisure activities are electricity-dependent, the relevance of electricity for leisure needs to be estimated. Based on time use statistics (Statistisches Bundesamt, 2015) and a boolean decision, whether the practise of a leisure activity relies on electricity or not, Wolf and Wenzel (2015) estimate for Germany that 65% of leisure activities are electricity-dependent. In this respect, however, we heuristically assume, that 50% of leisure activities are electricity-dependent (in accordance with e.g. Bliem, 2005; Growitsch et al., 2014; Piaszeck et al., 2014), since we view a boolean decision rather difficult[5]. In line with the literature, it is further assumed that the monetary value of each hour of leisure activity of an unemployed person amounts half the value of an employed person (e.g. Growitsch et al., 2014; de Nooij et al., 2009; Piaszeck et al., 2014; Wolf and Wenzel, 2015). Hence, based on the total population and the number of employed persons in a county c, the total GVA of the household sector in the respective county was quantified, and plugged into equation 1.

However, the gap between microeconomic theory and practise leads to a number of restrictions. Firstly, making use of average net wages per hour as a proxy for leisure-induced utility gains, may appear inappropriate for voluntary and involuntary unemployment (Piaszeck et al., 2014). Secondly, the assumption that employees can freely decide on their optimal amount of working time does not necessarily reflect reality in a work environment of union regulation and other traditional habits (Sanghvi, 1982). Thirdly, the value of leisure of unemployed persons also incorporates pensioners, children and homemakers, and it may be criticised that the value of leisure for such individuals is also determined based on the wages of the working population (Schröder and Kuckshinrichs, 2015). Finally, the approach does not take into account the possibility of switching to non-electricity dependent leisure activities in case of a blackout (Sanghvi, 1982).

Though, the application of the production function and the household income approach feature well-known disadvantages and limitations, the decisive advantage of making use of the sketched approaches in the context of this paper is that it allows an almost cost-free calculation of VoLLs on a high spatial resolution.

2.2 Value of Lost Load on Grid Operator Resolution

Determining the total economic value attached to the consumption of the electricity supplied by an operator's voltage level, requires information on the value of an average unit of electricity consumed from this voltage level. Since data on electricity consumption from the grid levels are reported by individual DGOs, the VoLL needs to relate to the same reference unit: the resolution of individual DGOs and voltage levels. Ideally, a bijective mapping needs to be performed, meaning that each unit of the electricity consumption, $\mathrm{EC}(s, c)$, of a sector s in a county c, is unambiguously assigned to a unit of electricity consumptions within a specified voltage levels v of a specified DGO o.

In general, the average VoLL of the electricity consumed within the voltage level v of a DGO o, $\mathrm{VoLL}(v, o)$, can be calculated from the electricity consumed within the respective voltage level of the operator, and the VoLLs attached to each kWh of this consumption. Let $\mathrm{EC}(s, c, v, o)$ name

[5] It is for example difficult to decide whether the reading of books and magazines requires electricity, since this significantly depends on whether electric light is required or not.

the (at the current step of the methodology) unknown fraction of electricity consumption $\mathrm{EC}(s,c)$ consumed in the voltage level v of DGO o by a sector s located in county c[6], then $\mathrm{VoLL}(v,o)$ can be determined from the sector- and county-specific VoLLs, $\mathrm{VoLL}(s,c)$, as calculated in the previous subsection:

$$\mathrm{VoLL}(v,o) = \frac{\sum_{s,c} \mathrm{VoLL}(s,c) \cdot \mathrm{EC}(s,c,v,o)}{\sum_{s,c} \mathrm{EC}(s,c,v,o)} \tag{2}$$

However, the latter mapping cannot be performed bijectively, since a substantial proportion of electricity consumption cannot be unambiguously assigned to a certain DGO's voltage level. Therefore, in the following subsections two different kind of mappings are conducted: One mapping for those parts of sectoral- and county-specific electricity consumption $\mathrm{EC}(s,c)$ which can unambiguously be assigned to a specific voltage level v of a specific DGO o: $\mathrm{EC}^{ua}(s,c,v,o)$. And a second mapping, for the remaining consumption, which could potentially be consumed within several voltage levels and/or several DGO's domains: $\mathrm{EC}^{a}(s,c,v,o)$[7].

In the following subsections, we elaborate on the mapping of the household sector's and the other economic sectors' electricity consumption from county to DGO- and voltage level resolution (subsections 2.2.1 and 2.2.3 respectively), and on how the average VoLL of the household sector and the remaining sectors with respect to the individual voltage levels of each DGO was determined (subsection 2.2.2 and 2.2.4 respectively).

2.2.1 Mapping of Household's Electricity Consumption

As indicated, it is not a straightforward task to combine structural grid data as published by each DGO, with VoLLs determined from macroeconomic data on county resolution. To be able to combine these data sets, both need to relate to the same reference unit. Hence, a harmonisation of the resolutions is required, which motivated a mapping of electricity consumption (attached with each sector's county-specific VoLL) from county to operator resolution. For this purpose, we made use of geographic intersections between counties and operators, as specified below.

The suggested methodology to determine the electricity consumption by households with respect to each DGO requires information on the population living in county c supplied by operator o: $P^{(u)a}(c,o)$. The superscript ua/a indicates whether population was unambiguously or ambiguously assigned from county c to operator o. We determined $P^{(u)a}(c,o)$ on the basis of a five step process as elaborated on in the following paragraphs. To facilitate understanding, the following nomenclature is introduced: Let C be a set of all counties and O be a set of all DGOs. $A(c)$ and $A(o)$ shall constitute the geographic domain of county $c\epsilon C$ and DGO $o\epsilon O$ respectively. Further, let $A(o,c)$ be the geographic intersection of county c and DGO o: $A(o,c) := A(c) \cap A(o)$. Further, $a(c)$, $a(o)$ and $a(o,c)$ denote the geographic domain size of $A(c)$, $A(o)$ and $A(o,c)$.

At the beginning of the five step process, those DGOs o were identified for which $a(o,c) > 0.99 \cdot a(c)$ holds. This condition implies that o is an (almost) complete subdomain of only one county c. Consequently, all inhabitants of c were unambiguously assigned to operator o.

In step two, those DGOs were identified which, in conjunction with any of those DGOs to which population has been assigned already in step one, exactly cover a county. Precisely formulated, this means: Assuming, that o_1 overlaps with county c_1 (overlapping area: $a(o_1,c_1)$), and that people from county c_1 had already been assigned to an arbitrary number of other DGOs o_j ($j \neq 1$) in step one (which means, that these o_j are (almost) completely geographically covered by county

[6] Consequently, the following inequality must hold: $0 \leq \mathrm{EC}(s,c,v,o) \leq \mathrm{EC}(s,c)$

[7] In consequence, for the sum of both, the following inequality holds: $\sum_{s,c} \mathrm{EC}^{ua}(s,c,v,o) + \sum_{s,c} \mathrm{EC}^{a}(s,c,v,o) \geq \mathrm{EC}(v,o)$, with $EC(v,o)$ being the amount of electricity consumed from voltage level v of operator o.

c_1). Then, the remaining population of c_1 (which has not yet an unambiguous link to any DGO) was unambiguously mapped to o_1. These conditions can be expressed in the following inequality:

$$a(o_1, c_1) + \sum_{\forall j \text{ of step 1}} (a(o_j, c_1)) \geq 0.99 \cdot a(c_1)$$

Thereafter, in step three, we made use of population reporting on municipality resolution[8]. Analogously to step one, the population of a municipality was mapped onto a county o, if its geographic intersection is at least 99% of the municipality's domain size.

In step four, we mapped those population numbers, which have not been unambiguously assigned to any DGO yet. Based on the size of the geographic intersection with the overlapping counties, a maximum number of people from each county was determined, which could potentially consume from that specific DGO. This maximum number of people was constrained either by the total number of people living in the county domain which have not been unambiguously mapped onto another DGO yet or by a maximum population density of 5000 inhabitants/km^2. The second constraint prohibits that small geographical intersections exert unrealistic influence on the calculation[9].

After these four steps, onto each DGO a certain population number has been (un)ambiguously mapped from counties to operators ($P^{ua}(c, o)$ and $P^{a}(c, o)$). For some operators it was possible to further increase the share of unambiguously mapped population; namely in those instances where the difference between unambiguously assigned population and the total population supplied by a specific DGO, can only be explained if a certain fraction of the so-far ambiguously assigned population, $P^{\text{a}}(c, o)$, is instead unambiguously assigned to the same operator. Mathematically, this implies that as long as the inequality

$$\left(\sum_c P^{ua}(c, o)\right) + \left(\sum_c P^{\text{a}}(c, o)\right) - P^{a}(c, o) < P(o)$$

holds (with $P(o)$ being the number of people supplied by each DGO), population was shifted from $P^{a}(c, o)$ to $P^{ua}(c, o)$.

2.2.2 Value of Lost Load of the Household Sector

Having determined unambiguous and ambiguously mapped population information, $P^{(u)a}(c, o)$, constitutes the basis for calculating the electricity consumed by the household sector (which is required to determine the VoLL via Eq. 1). In this analysis, the households' electricity consumption was determined from the county-specific per-capita electricity consumption in each county, $e_{p.c}(c)$, and the population living in county c supplied by operator o, $P(c, o)$. Considering that the household sector ($s ='\text{HH}'$) withdraws its electricity from the low-voltage grid ($v ='\text{LV}'$), the electricity (un)ambiguously consumed by those households which are located in a certain county c and which are supplied by operator o were calculated from:

$$\text{EC}^{(u)a}_{s='\text{HH}',\, v='\text{LV}'}(c, o) = \text{P}^{(u)a}(c, o) \cdot e_{p.c}(c). \tag{3}$$

In the following equations, we have shortened the subscripts, which indicate that electricity consumption refers to the household sector and the low voltage level, from "s = 'HH', v = 'LV'" to "HH, LV". Based on this convention and the latter equation, the total electricity consumed by the household sector was determined from:

[8] Each county is subdivided into at least one municipality. In Germany there are about 11,300 of the latter.

[9] This constraint was chosen heuristically, derived from the population density of the most densely populated municipality in Germany, which is 4,601 persons/km^2 (Federal Statistical Offices, 2015).

$$\mathrm{EC}_{\mathrm{HH,LV}}(o) = \underbrace{\sum_c \mathrm{EC}^{ua}_{\mathrm{HH,LV}}(c,o)}_{=:\mathrm{EC}^{ua}_{\mathrm{HH,LV}}(o)} + \underbrace{\mathrm{P}^a(o) \cdot \frac{\sum_c g_1(c) \cdot \mathrm{P}^a(c,o) \cdot e_{p.c}(c)}{\sum_c g_1(c) \cdot \mathrm{P}^a(c,o)}}_{=:EC^a_{\mathrm{HH,LV}}(o)} \tag{4}$$

Note that $\mathrm{P}^a(o)$ is defined as $(\mathrm{P}(o) - \sum_c \mathrm{P}^{ua}(o,c))$, which is the number of people supplied by operator o not unambiguously assigned to any county. The weighting factor $g_1(c)$ is determined by the ratio between the number of people living in county c which are not unambiguously assigned to any operator o, and the sum of all people living in county c which are ambiguously assigned to any operator: $g_1(c) = (P(c) - \sum_o \mathrm{P}^{ua}(o,c)) \,/\, (\sum_o \mathrm{P}^a(o,c))$. There are two reasons for including this weighting factor: Firstly, the probability that a person is actually consuming its electricity from an ambiguously assigned DGO is much higher, if it is ambiguously assigned to few other operators only, and vice versa. The second reason is a conservation rationale; to keep the Germany-wide average VoLL of the household sector constant, when transforming the spatial resolution of VoLL values from county- to DOG-resolution. Without incorporating $g_1(c)$, an individual county ambiguously assigned to several DGOs would exert larger influence on the German average VoLL of the household sector then another one which is assigned to a very small number of DGOs only.

Based on the VoLL of electricity consumption in the assigned counties (calculated from macroeconomic data),$\mathrm{VoLL}_{\mathrm{HH}}(c)$, the VoLL of unambiguously and ambiguously assigned electricity consumption in the domain of an operator was determined:

$$\mathrm{VoLL}^{ua}_{\mathrm{HH,LV}}(o) = \frac{\sum_c \mathrm{EC}^{ua}_{\mathrm{HH,LV}}(c,o) \cdot \mathrm{VoLL}_{\mathrm{HH}}(c)}{\sum_c \mathrm{EC}^{ua}_{\mathrm{HH,LV}}(c,o)} \tag{5}$$

$$\mathrm{VoLL}^{a}_{\mathrm{HH,LV}}(o) = \frac{\sum_c g_1(c) \cdot \mathrm{EC}^{a}_{\mathrm{HH,LV}}(c,o) \cdot \mathrm{VoLL}_{\mathrm{HH}}(c)}{\sum_c g_1(c) \cdot \mathrm{EC}^{a}_{\mathrm{HH,LV}}(c,o)} \tag{6}$$

Based on the previous equations, the household sector's mean VoLL can be determined straightforwardly from the arithmetic mean:

$$\overline{\mathrm{VoLL}}_{\mathrm{HH,LV}}(o) = \frac{\mathrm{EC}^{ua}_{\mathrm{HH,LV}}(o) \cdot \mathrm{VoLL}^{ua}_{\mathrm{HH,LV}}(o) + \mathrm{EC}^{a}_{\mathrm{HH,LV}}(o) \cdot \mathrm{VoLL}^{a}_{\mathrm{HH,LV}}(o)}{\mathrm{EC}_{\mathrm{HH,LV}}(o)} \tag{7}$$

Due to the partially ambiguous mapping of population from counties to operators, the average VoLL as determined with Eq. 4 is characterised by uncertainty. The uncertainty increases the larger the fraction of households supplied by o whose county-affiliation is ambiguous, and the larger the spread of the individual VoLLs of the household sector among these ambiguously assigned counties. To quantify uncertainty, we determined the minimum and maximum values of the VoLL of the household sector of operator o. For this purpose, the difference between reported population supplied by a DGO and the unambiguously mapped population, $P(o) - \sum_c \mathrm{P}^{ua}(o,c)$, was bridged with those ambiguously mapped population, that minimises/maximises the VoLL of the ambiguously assigned electricity consumption $\mathrm{VoLL}^a(v,o)$.

Further, it has to be mentioned that not only the average VoLL but also the amount of electricity consumed by the household sector (as determined with Eq. 4) is characterised by uncertainty. This uncertainty is driven by the variability of the per-capita electricity consumption $e_{p.c.}$. Since data on the latter are available on the spatial resolution of federal states only (compare chapter 3), $e_{p.c.}$varies only with respect to different federal states. Hence, the electricity consumption of households within the domain of a certain DGO is only attached with uncertainty, if the ambiguously assigned population live in different federal states. Therefore, we found that the induced uncertainty of the households' electricity consumption is comparably negligible in its effect on the uncertainty attached to the VoLL of the low-voltage level, and, therefore, neglect uncertainty of the amount of electricity consumed by households.

2.2.3 Mapping of other Economic Sectors' Electricity Consumption

Based on the determination of total electricity consumption by household, the remaining electricity consumption to be assigned to the remaining economic sectors was determined. For these sectors, in analogy to the assignment of the population data, an unambiguous and an ambiguous mapping based on geographic overlaps was performed. However, for most of the other economic sectors it is unclear from which voltage level the electricity is consumed. Therefore, the fraction of ambiguously mapped electricity is significantly larger than for the household sector. The heuristic rationales according to which the mapping was performed is the following: (a) The *manufacturing & mining* sector withdraws the majority of its electricity supply from the higher voltage levels (high and medium voltage grid). (b) The sectors *agriculture* and *services* withdraw the majority of its electricity supply from the low and medium voltage grid. (c) The higher the geographic intersection between a county and a DGO, the higher the probability that sectors located in c consumed its electricity from the intersecting DGO o. (d) Only for the construction sector, we unambiguously map onto the low voltage level (in case the DGO was certain).

We operationalise the previous observations as follows: Based on (d) and (c), it was assumed that when the geographic intersection area $a(c,o)$ is above 80% (90%, 95%, 99%) of $a(c)$, 15% (30%, 60%, 100%) of electricity consumption by the construction sector can be unambiguously assigned to the low-voltage grid of the respective DGO o. The remaining 85% (70%, 40%, 0%) were mapped unambiguously onto the low-voltage grid. From (a) and (b) follows, that an unambiguous mapping is not possible for the remaining sectors, due to the uncertainty from which voltage level these sectors consume electricity. Hence, these sectors' electricity consumption was ambiguously mapped in the following manner: (i) we ambiguously mapped 100% of the electricity consumed in county c by the agricultural and the services sector, and 10% of the manufacturing & mining sector onto the low voltage level of the respective geographically intersecting operator o; (ii) we ambiguously mapped 100% (100%, 100%) of the electricity consumed in county c by the agricultural (services, manufacturing & mining) sector onto the medium voltage level of the respective operator; (iii) we ambiguously mapped 10% (10%, 100%) of the electricity consumed in county c by the agricultural (services, manufacturing & mining) sector onto the high voltage level of operator o. We reflect issue (c) by reducing the maximum amount of electricity ambiguously assigned to a DGO o, if the geographic intersection ratio $a(c,o)/a(c)$ is small: Concretely, in case of a geographic intersection ratio $a(c,o)/a(c)$ of less than 20% (10%, 5%, 1%), not more than 60% (40%, 20%, 10%) of the electricity consumption of economic sectors in county c were assigned to the consumption from any voltage level of the geographically intersecting DGO o.

Finally, in analogy to step five of the mapping of population data (subsection 2.2.1), the share of unambiguously mapped electricity consumption was increased by shifting fractions of so-far ambiguously assigned electricity consumption to the unambiguously assigned consumption. This can be performed for those ambiguously assigned electricity consumptions $EC^{\mathrm{a}}(s,c,v,o)$ for which the following inequality holds:

$$\left(\sum_c EC^{\mathrm{ua}}(s,c,v,o)\right) + \left(\sum_c EC^{\mathrm{a}}(s,c,v,o)\right) - EC^{\mathrm{a}}(s,c,v,o) < EC(v,o)$$

with $EC(v,o)$ being the total electricity consumption from voltage level v of operator o.

2.2.4 Value of Lost Load of other Economic Sectors

Based on the mapping as elaborated on in the previous subsection, the average VoLL for the unambiguously mapped electricity consumption, $\mathrm{VoLL}^{ua}(v,o)$, was calculated via Eq. 2. In analogy to the average VoLL of the ambiguously mapped electricity consumption by households, the calculation of the average VoLL of ambiguously mapped electricity consumption by the four economic sectors considered how often a specific kWh is ambiguously attributed to a certain DGO and/or voltage level. This is accounted for by adding a weighting factor, $g_2(s,c)$, into Eq. 2, which constitutes the probability that the ambiguously mapped electricity consumption $\mathrm{EC}^a(s,c,v,o)$ is actually consumed within voltage level v of operator o:

$$\mathrm{VoLL}^a(v,o) = \frac{\sum_{s,c} g_2(s,c) \cdot \mathrm{EC}^a(s,c,v,o) \cdot \mathrm{VoLL}(s,c)}{\sum_{s,c} g_2(c) \cdot \mathrm{EC}^a(s,c,v,o)}, \tag{8}$$

We determined $g_2(s,c)$ from the ratio between the amount of electricity consumed by a sector s in county c which remains to be assigned after the unambiguous mapping, $\mathrm{EC}(v,o) - \sum_{v,o} \mathrm{EC}^{ua}(s,c,v,o)$, and the sum of all ambiguously mapped electricity consumption from the same sector and county, $\sum_{v,o} \mathrm{EC}^a(s,c,v,o))$. Hence, $g_2(s,c)$ reads:

$$g_2(s,c) = \frac{\mathrm{EC}(v,o) - \sum_{v,o} \mathrm{EC}^{ua}(s,c,v,o)}{\sum_{v,o} \mathrm{EC}^a(s,c,v,o)}$$

The weighting factor $g_2(s,c)$ was incorporated into Eq. 8 for the same two reasons for which $g_1(c)$ was added as a weighting factor when determining the average VoLL of the household sector via Eq. 7: Firstly, to account for the fact that the probability that a kWh is actually consumed in an (ambiguously) assigned DGO is much higher, if it is ambiguously assigned to few others only, and vice versa. Secondly, it is required to keep the Germany-wide average VoLL independent of the mapping process.

Finally, based on the VoLL of the unambiguously mapped electricity (as determined with Eq. 2), and ambiguously mapped electricity (as determined with Eq. 8), $\mathrm{VoLL}^{ua}(v,o)$ and $\mathrm{VoLL}^a(v,o)$ respectively, the mean VoLL for a certain v,o-combination was determined:

$$\overline{\mathrm{VoLL}}(v,o) = \frac{\mathrm{VoLL}^{ua}(v,o) \cdot \mathrm{EC}^{ua}(s,c) + \mathrm{VoLL}^a(v,o) \cdot (\mathrm{EC}(v,o) - \mathrm{EC}^{ua}(v,o))}{\mathrm{EC}(v,o)},$$

with $\mathrm{EC}^{ua}(v,o) := \sum_{s,c} \mathrm{EC}^{ua}(s,c,v,o)$. As for the calculation of the mean VoLL of the household sector, due to the partially ambiguous mapping, the mean VoLL is characterised by uncertainty. Analogously, minimum and maximum values of the VoLL of each voltage level and operator were determined.

2.3 Value of Lost Grid

As stated in the introductory section, the VoLL concept does not serve as a meaningful quantity to determine optimal economic levels of supply security, as argued by Welle and Zwaan (2007), since a quantitative analysis of the economic value of a grid requires information not only on the economic value generated by a unit of delivered electricity, but also on the amount of electricity consumed and the infrastructure needed to generate the respective economic value. This methodological gap motivated the introduction of a new measure, to which we refer as Value of Lost Grid (VoLG), and on which we will further elaborate in the following.

The general idea was, to relate the economic value generated due to the steady supply of electricity by a certain grid infrastructure to the infrastructure needed to enable that steady supply. In a first step, the total economic value generated by a voltage level of a DGO can be concluded from the VoLL as calculated in the previous subsections: Based on the unambiguously and ambiguously assigned electricity consumption of the individual economic sectors within a certain grid domain, a minimum, mean and maximum VoLL was calculated for each DGO and for each voltage level (as outlined in subsection 2.2). Based thereon, the total value generated within a certain voltage level of a certain operator depends on the total amount of electricity consumed from the respective voltage level in a defined period of time, $\mathrm{EC}(v,o)$. Accordingly, the total value generated within that time horizon can be calculated from $\mathrm{VoLL}(v,o) \cdot \mathrm{EC}(v,o)$.

Next, a useful reference parameter needs to be selected, that captures the infrastructure requirements to distribute electricity, which in turn contributed to the estimated generated economic value. From those quantities which are publicly available, the total grid length of a certain voltage level as well as the necessary transformer station capacities between the voltage levels are potential meaningful proxy variables. However, as there is no objective way of combining both into one reasonable quantity, this study uses the total grid length of a certain voltage level as reference quantity, since it probably captures the infrastructural requirements in the most meaningful manner. Based on the minimum-, maximum- and mean-value of the VoLL of a certain voltage level of a certain DGO, $\mathrm{VoLL}_{\mathrm{min/mean/max}}(v,o)$, the VoLG was determined via:

$$\mathrm{VoLG}_{\mathrm{min/mean/max}}(v,o) := \mathrm{VoLL}_{\mathrm{min/mean/max}}(v,o) \cdot \frac{\mathrm{EC}(v,o)}{L(v,o)}, \tag{9}$$

with $L(v,o)$ being the grid length of voltage level v of operator o.

Based on these minimum and maximum values a measure is introduced that mirrors the uncertainty induced by the partially ambiguous mapping process: Based on the ambiguously assigned electricity consumption and its determined VoLL a probability distribution function (pdf) of the VoLL of a random kWh of electricity can be determined. This, however, does not constitute a useful measure to quantify the uncertainty attached to the actual amount of electricity consumed, which can be illustrated by the following example: Assume that the low voltage grid of a certain DGO delivered 10 GWh of electricity annually. The mapping process enables to determine for 7 GWh, which sectors in which county unambiguously consumed from this DGO's grid. Assume a scenario, according to which for the remaining 3 GWh, a number of sectors, whose consumption add up to 4 GWh, potentially (ambiguously) consumed from that specific operator. The uncertainty attached to the VoLL of the 3 GWh is certainly much lower, compared to another scenario (with identical VoLL pdf), where the ambiguously assigned consumption amounts 40 GWh instead of 4 GWh. Hence, the pdf of the VoLL of a random kWh of electricity of the ambiguously assigned electricity consumption does not constitute a meaningful measure. Due to the discrete nature of this mathematical problem, we cannot resort to the mathematics of combinatorics to determine a probability distribution of the resulting VoLL or VoLG for a voltage level of a DGO. In consequence, this study opted for minimum and maximum values of VoLL and VoLG as a measure of uncertainty in the way already described . In order to facilitate a quick comparison between uncertainties attached to the mean VoLG, we further determined the relative average deviation of minimum and maximum from the mean value: $d = 1/2 \cdot (\mathrm{VoLG}_{max} - \mathrm{VoLG}_{min})/\mathrm{VoLG}_{mean}$.

It has to be noted, that in this study the electricity consumption from the transformation stations was attributed to the respective upper voltage level[10]. The reasoning for this approach is that the upper voltage level is required to transport the electricity to the substations. Hence, substations are treated as any other consumer from the respective level.

Further, when calculating the VoLG of a certain voltage level, the electricity consumption from the respective lower voltage levels was included. This means that the value generated within the low voltage level, was added to the value of the electricity directly withdrawn from the medium voltage level. One could argue to not consider the share of electricity which is directly induced by small-scale generation units into the low voltage level, when calculating the VoLG for the medium voltage level. However, a stable operation of the electricity grid as an interconnected network requires a continuous connection to the respective upper voltage levels as a buffer to balance differences

[10] We for example attributed the electricity consumption from the substations between the low voltage and medium voltage level to the medium-voltage level.

between supply and demand in the lower voltage levels. Hence, an interrupted electricity transfer for example in the medium-voltage level may trigger interrupted supply in the low-voltage level, which is not only constrained to the electricity which was delivered by the medium voltage level.

3 Data

In order to account for the large interregional heterogeneities of the VoLL (compare Growitsch et al., 2014; Piaszeck et al., 2014; Wolf and Wenzel, 2015), this study targeted to calculate the latter at county resolution, which is the highest possible resolution achievable with available macroeconomic data. For Germany, VoLLs on this spatial resolution were determined by Piaszeck et al. (2014) and Wolf and Wenzel (2015). Therefore, the data sources used in this study to calculate VoLLs on county resolution, are mostly in line with the data sources of the latter authors. However, this study resorts to updated data where available and slightly deviated from certain assumption, as outlined in the following subsection. To determine VoLLs for the five different sectors (four economic sectors plus households) on county resolution, not all necessary data are widely available. Therefore, in some cases proxy data or data from a more coarse spatial resolution were employed.

3.1 VoLL on County Resolution

Data on the county-specific gross values added (GVA) by each of the four economic sectors are published in the regional statistics of the German Federal Statistical Office. Data on electricity consumption within each county are published only for the *manufacturing & mining* sector by the same authority. It has to be noted that for reasons of confidentiality or a lack of data, this data set is incomplete with respect to five counties[11]. For the remaining three sectors, the county- and sector-specific electricity consumption is approximated from national average VoLLs of these sectors. These national average VoLLs are calculated from the Germany-wide electricity consumption and the GVA of the respective sectors. Data on both can be deduced from the energy balance sheets of Eurostat and the national accounts of the German Federal Statistical Office respectively.

Though, data on electricity consumption are available on county resolution for the *manufacturing & mining* sector, sector-specific VoLLs cannot be calculated in a straightforward manner, since the data on GVA also subsumes the energy sector, which is not included in the data on electricity consumption. Hence, the GVA by the energy sector is subtracted in a two-step process, as applied by Piaszeck et al. (2014) and Wolf and Wenzel (2015): Information on the GVA by the energy sector is only available on federal states's level in the national accounts of the federal states (available via the Federal Statistical Office). Therefore, in a first step, the GVA by the energy sector is allocated to the counties within the respective federal state according to the share of energy sector employees working in a county. Employee data were purchased from the German Employment Agency. Due to the fact that some of these data were made anonymous for reasons of confidentiality, a second step is needed, in which the remaining share of federal GVA is allocated to the remaining counties in proportion to the number of companies active in the sector (data can be accessed via the regional statistics of the Federal Statistical Office).

The highest available resolution of data on electricity consumption of the household sector is at federal states level via the federal states' statistical offices. At the date of data compilation, the

[11]Four of these are located in Brandenburg: Oberhavel, Uckermark, Märkisch Oderland, Brandenburg an der Havel; the fifth in Lower Saxony: Wolfsburg. For the four of the counties located in Brandenburg, electricity consumption was estimated based on the average VoLL of the sector in Eastern Germany. Energy consumption in the fifth non-reported county, Wolfsburg, was estimated based on the VoLL of the Transport Equipment industry in Lower Saxony as determined by Growitsch et al. (2014).

data's reference years varied amongst the authorities, and four federal states (Bavaria, Bremen, Hesse and Saarland) did not report on electricity consumption by households individually. Of the remaining, all but two federal states report at least on 2013 electricity consumption by households (North Rhine-Westphalia reports until 2012, Rhineland-Palatinate until 2011). For these two, 2012 and 2011 values were used instead. For the four non-reporting states, electricity consumption at federal level was approximated by distributing the remaining national consumption according to population numbers and household sizes[12]: for each federal state the number of one-person-equivalent-households[13] was calculated. Data on the ratio of average electricity consumption of households of different size, were taken from (BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2014); data on population and household size in the different federal states were deduced from the German Federal Statistical Office. Finally, household electricity consumption at county level was approximated by distributing the federal consumption amongst the counties proportionally to the county's population numbers[14].

In oder to determine the value of leisure (i.e. of household electricity consumption), county-specific net wages per employee are calculated from gross average wages, which are available via the national accounting of the Federal Statistical Office. In analogy to the discussed literature (e.g. Growitsch et al., 2014; Piaszeck et al., 2014; Wolf and Wenzel, 2015), net wages are assumed to equal half of the gross wages. Moreover, data on the total number of working hours by the population living in a county is required, but the Workforce Accounts of the Federal Statistical Office only provides data on the number of working hours of all employees *working* in a county. In order to consider commuting flows, data on working hours are multiplied by the ratio of employees living in the county over employees working in the county[15]. Both latter data sets are available via the workforce accounts of the Federal Statistical Office.

The time remaining to be devoted to leisure activities and work is estimated from data on the time needed for personal activities, such as sleeping, eating or washing (which can be found in Statistisches Bundesamt, 2015). Accordingly, an average German employee devotes 10.58 hrs (10:35 hrs:min) to these personal activities. Unemployed & non-working persons, pensioners, and young people aged below 16 years devote 11:29, 11:49 and 10:35 hrs:min respectively to these activities. Based on these data, we assumed that during a year, employees may devote $(24 - 10.58) \cdot 365$ hrs to leisure activities and work, whereas non-employed people may devote $(24 - 11.5) \cdot 365$ hrs on leisure activities[16].

3.2 VoLG on Operator Resolution

The mapping of electricity consumption from county resolution to DGO resolution required geo-information of counties, municipalities and DGOs. The shape of the DGOs' domains at the reference date of 01.01.2016 was purchased from a geomarketing consultancy (Lutum + Tappert DV-Beratung GmbH, 2016); Geo-information of German counties and municipalities are available via the GADM database (Gadm.org, 2015); Population data on municipality resolution are available via the federal statistical offices at the reference date of 31.12.2014. We additionally considered changes in municipality domains in the course of 2015 based on the reporting of the

[12]In this respect, we deviate from Piaszeck et al. (2014) and Wolf and Wenzel (2015) which considered total population size only.

[13]This accounts for the fact that a one-person-household consumes more electricity per person then a two-person-household.

[14]Here, household sizes cannot be taken into account, since these data are unavailable on county resolution.

[15]This implies the assumption that the working hours of an employee living in a county are the same as the working hours of an employee commuting to that county.

[16]Hence, we slightly deviate from e.g. Growitsch et al. (2014) and Piaszeck et al. (2014), who used 11 hours for both groups.

statistical federal offices, to avoid inconsistencies related to the different reference period of county shapefiles and municipality population records.

From the DGOs' legal reporting obligations, we deduced the grid lengths of each voltage level, the total annual electricity consumption per voltage level, the total annual electricity withdrawal of a certain voltage level from the upstream voltage level as well as the population number supplied. The electricity consumption from each voltage level was determined from the difference between total annual electricity consumption (which usually includes the supply to lower voltage levels), and the annual electricity withdrawal of the respective lower voltage level from the upper one. The reported grid length of the low voltage grid include house connections to the households.

Due to the large number of DGOs in Germany (almost 900), a basic data set of structural grid data was purchased via the mentioned geomarketing consultancy (Lutum + Tappert DV-Beratung GmbH, 2016) from the *Get AG*. These data set is mostly based on the operators' reporting with respect to the reference year 2012[17]. However, for this study, if available, data was updated to the most recent reporting period at the date of data collection (commonly: reference year 2015) for those DGOs which provide electricity to at least 100,000 inhabitants, plus all those operators which were non-existent at the time the GET AG data set was compiled, and if operators merged, split up or renamed.

The data of the GET AG data base, as well as those additionally collected were subjected to plausibility checks[18]. Due to inconsistencies in the reporting and non-compliance with the legal reporting obligations, data sets could not fully be compiled for all DGOs. 38 DGOs for example did not include house connection in the reporting of grid lengths of the low voltage grid as legally obliged. However, since 24 DGOs in the data set reported on both (the grid length including and excluding house connection lines), these data were used to determine an average ratio between grid lengths including house connection lines and grid length without. Based on this ratio, those data which did not include house connections were scaled. Finally, it has to be mentioned that the required data to determine the voltage-level specific electricity consumption were not available for 78 DGOs.

4 Results

In this analysis, the ratio between the economic value of electricity consumed and the infrastructure needed to deliver that economic value is investigated. Since, the fundamental assumptions and macroeconomic data gathered to determine county- and sector-specific VoLLs are largely in line with Piaszeck et al. (2014) and Wolf and Wenzel (2015), our outcomes are in very good agreement with the results of these authors: Firstly, national VoLLs for the sectors *agriculture*, *construction* and *services* of 2.22 €/kWh, 125.30 €/kWh and 12.67 €/kWh respectively are consistent with their results. Secondly, patterns of regional VoLLs on county resolution of both, the household sector as well as the county-average of all remaining other economic sectors (compare Fig.1), quantitatively compare well with the county-resolved VoLLs as published in Piaszeck et al. (2014). Hence, we may reinforce their finding, that the VoLL is subjected to significant interregional heterogeneities.

[17] In some cases, the reference year of published company information was older than the date at which the data had been collected by the Get AG.

[18] For example double-checking unexpectedly high or low values of e.g per-capita electricity consumption and investigate infringements with energy conservation

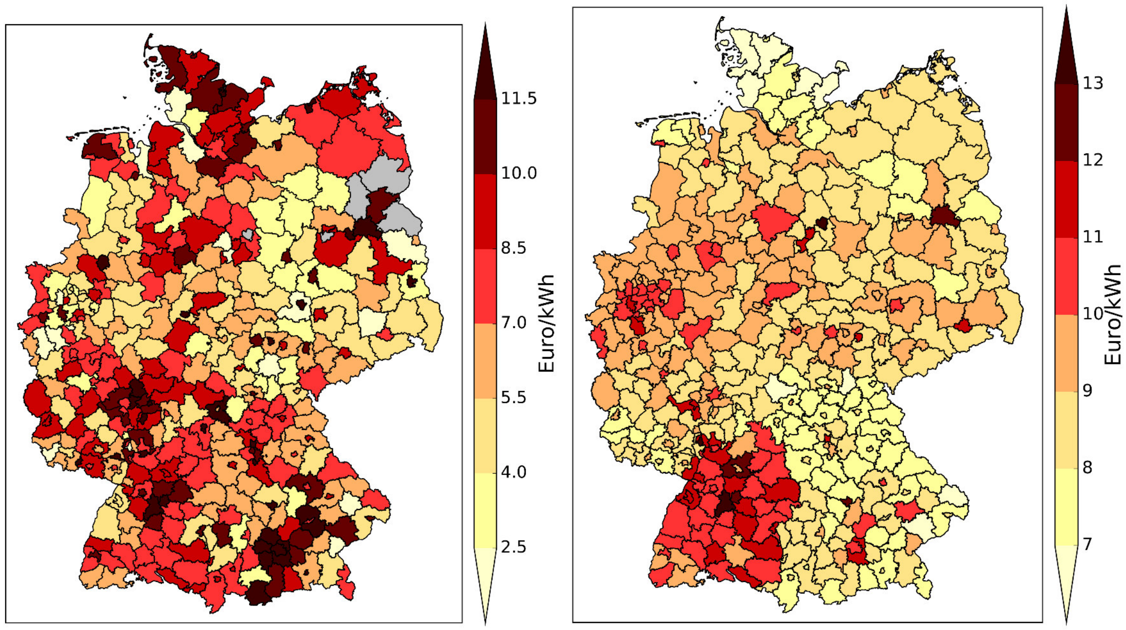

Figure 1: Value of Lost Load (VoLL) in €/kWh at county resolution. Left: Average VoLL of the four economic sectors; Right: VoLL of household sector. Grey indicates a lack of data.

As already indicated, the calculation of VoLLs on voltage level- and DGO spatial resolution required a mapping of electricity consumption on county resolution onto individual voltage levels and operators. This mapping could only partially be performed unambiguously. Therefore, we shortly elaborate on the degree of how much electricity was actually unambiguously mapped, since it greatly influences how precisely the VoLL can be determined on the spatial resolution of operators. Due to the fact that population data are resolved on municipality level and are, thus, available on a spatial resolution which significantly exceeds the resolution of counties[19], a very large share of the household sector's electricity consumption was unambiguously assigned: In course of the mapping process, 71.2 million inhabitants (approx. 88% of the total German population) were unambiguously assigned to a specific DGO. However, this share significantly varied amongst the operators[20]. The household sector significantly contributes to the electricity consumption from the low-voltage grid and accounts for a markedly 73.4%-share of electricity consumption from the low-voltage level[21]. This high share of unambiguous mapping was not observed for the medium-voltage grid. In total, only 7.2% of total electricity consumption consumed from the medium-voltage level was ambiguously mapped[22].

Having introduced the relative average deviation d of minimum and maximum VoLG from the mean VoLG (see subsection 2.3) implies the advantage, that mean VoLGs can be more easily illustrated in conjunction with the uncertainty attached to the mean value, as illustrated in Figs. 2 and 3 for the low and medium voltage grid. There are a few general observations which can be drawn from these figures. Firstly, the difference in the scaling of the colourcode signals at first

[19]Germany is subdivided into around 400 counties or around 11300 municipalities.

[20]Sorted by the share of unambiguously assigned population, the central 90% of operators are characterised by an assignment ratio ranging from 56% to 100%.

[21]According to our calculations, the household sector consumes between 50.0% and 95,3% (range given for the central 90% of operators) of electricity from the low-voltage grid of an individual DGO.

[22]Again, this ratio experiencing a significant variation from 0.00% (5th percentile) to 56.10% (95th percentile).

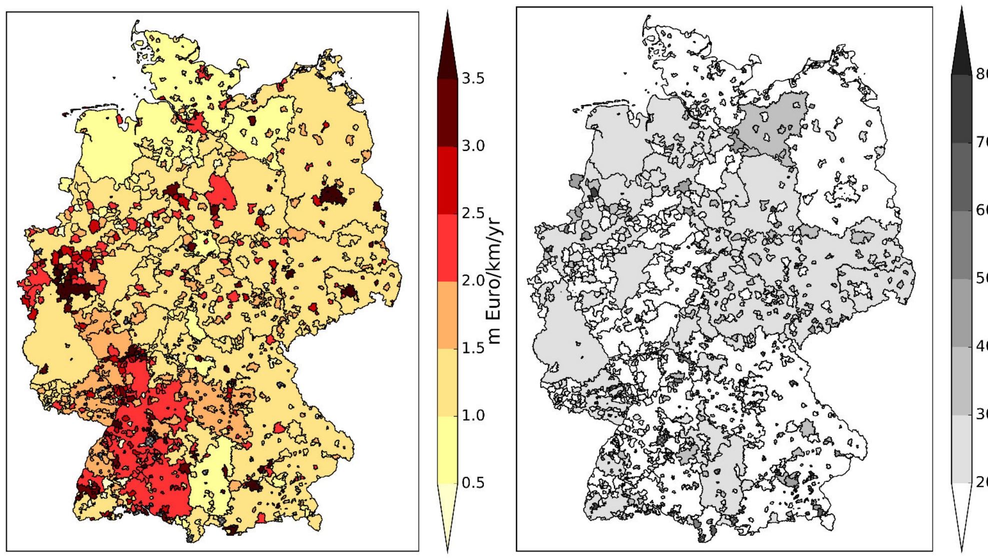

Figure 2: Low voltage grid: Value of Lost Grid (VoLG) in million €/km/yr within individual distribution grid domains (left figure), and the uncertainty attached to it (right figure) expressed as the relative average deviation d of minimum and maximum VoLG from the mean VoLG in each grid domain ($d = 1/2 \cdot (\text{VoL}G_{max} - \text{VoL}G_{min})/\text{VoL}G_{mean}$). Hatched grey-coloured domains indicate lacking data.

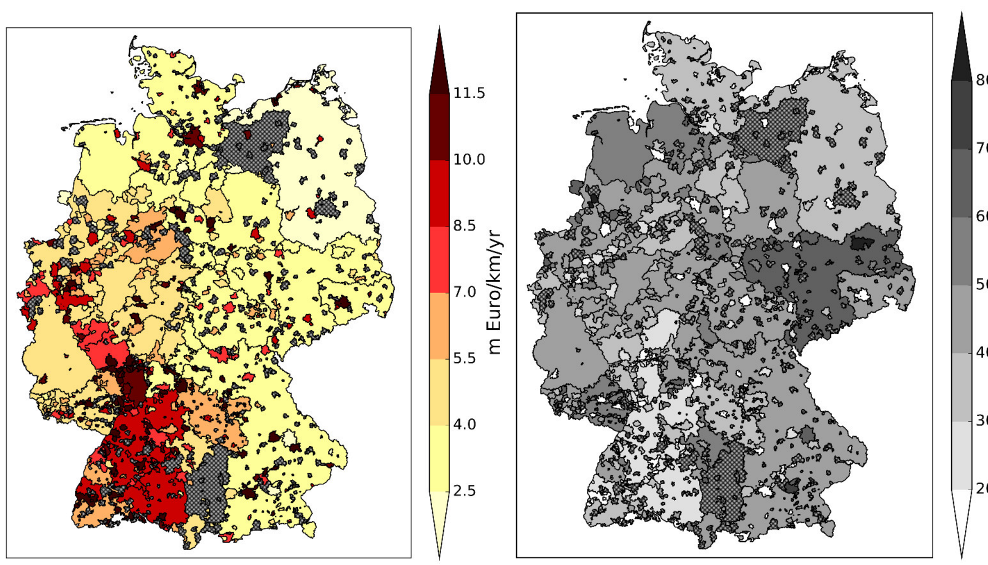

Figure 3: Medium voltage grid: Value of Lost Grid (VoLG) in million €/km/yr within individual distribution grid domains (left figure), and the uncertainty attached to it (right figure) expressed as the relative average deviation d of minimum and maximum VoLG from the mean VoLG in each grid domain ($d = 1/2 \cdot (\text{VoL}G_{max} - \text{VoL}G_{min})/\text{VoL}G_{mean}$). Hatched grey-coloured domains indicate lacking data.

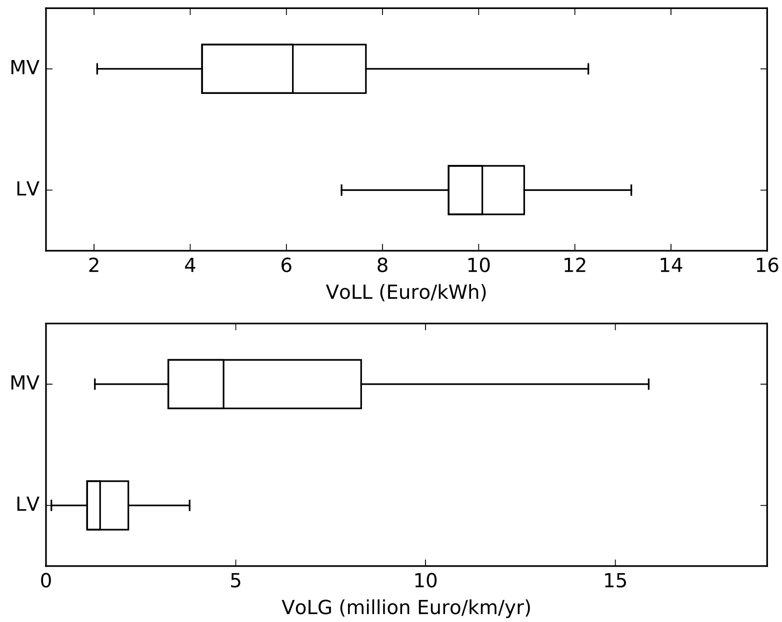

Figure 4: Box-and-Whisker plots (excluding outliers) of average VoLLs (upper figure) and VoLGs (lower figure) for the low voltage (LV) and medium voltage (MV) grid. The central box indicates the VoLL/VoLG range of the central 50% of the total electricity consumption of the respective voltage level.

sight that in general the VoLGs in the medium voltage level is significantly above the VoLGs in the low voltage level. Secondly, the variability of the colours indicates a pronounced interregional heterogeneity of VoLGs for both voltage levels. Thirdly, the uncertainty of the VoLG is more pronounced in the medium than in the low voltage level. In the following, we will focus on these three observations in more detail:

Since the higher voltage levels in general have higher capacities to transport electricity, we anticipated the VoLG in the medium voltage level to be higher than in the low voltage level. The lower box plot in Fig. 4 specifies the difference between the VoLG in the low and medium voltage level; Accordingly, the median VoLG of the low-voltage grid of 1.43 million €/km/yr is markedly below the median VoLG of the medium voltage grid of 4.68 million €/km/yr. However, the upper box plot in Fig. 4 reveals, that the VoLL of electricity directly consumed from the medium voltage grid is substantially lower than electricity withdrawn from the low-voltage grid. Therefore, one may conclude that the difference between the two voltage levels with respect to the VoLG results from a high ratio of electricity consumption to grid length, and is moderated by a countervailing characteristic of the VoLL.

With respect to the regional variability of the VoLG, Figs. 2 and 3 illustrate, that the South-West and certain Western parts of Germany are characterised by comparably high VoLGs in both analysed voltage levels. Moreover, many smaller operators have considerable high VoLGs. Comparing results on the VoLG to data illustrating the ratio of electricity used per voltage level over area of the DGO's domain (kWh/km^2), illustrate a positive correlation between the two quantities (not displayed in this study). Moreover, comparing the interquartile ranges (IQR) of VoLLs and VoLGs in Fig. 4 illustrates that the interregional heterogeneity of the VoLG is markedly higher than heterogeneity of the VoLL[23]. In addition, the IQR of the VoLGs is markedly more pronounced in the medium voltage level then in the low voltage level.

Comparing Figs. 2 and 3 illustrates that the uncertainty attached to the VoLGs is comparably larger with respect to the medium voltage level. Hence, information deduced from the VoLG calculations of the medium voltage grid is less precise, than the conclusions that can be drawn from the VoLGs calculated for the low voltage grid. However, due to the fact that mean VoLGs in the medium voltage grid may differ up to an order of magnitude (compare lower box plot in Fig. 4), a comparison between operators is still meaningful, especially having in mind, that the uncertainty measure introduced is based on the maximum possible deviation from the determined mean value.

5 Discussion and Conclusions

Based on macroeconomic data, the VoLL in Germany can be determined on varying sectoral and spatial resolutions: Piaszeck et al. (2014) and Wolf and Wenzel (2015) determined the VoLL on the spatial resolution of German counties for five different sectors and showed that the VoLL is characterised by pronounced regional heterogeneity. The authors have analysed their results in the context of potential future scenarios of electricity scarcity to enable cost-efficient load-shedding (intentional power shutdowns). This study, however, applies the VoLL methodology as a starting point to investigate differences in the economic value of the electricity distribution grid infrastructure, in order to facilitate cost-efficient decision making with regard to grid extension requirements and altering climatic conditions.

Since a quantitative analysis of the relative economic value of a grid requires information not only on the economic value generated by a unit of delivered electricity, but also on the amount of electricity consumed and the total infrastructure needed to generate the respective economic value, we proposed the VoLG concept as a basis for assessing climate change induced economic risks on the grids. Based on this approach, the total economic value associated with the electricity consumed from a DGO's voltage level was determined (including a measure indicating the uncertainty attached) and related to the grid length of the respective voltage level.

In principle, our results allow an operator- and voltage level-specific analysis of the relative economic value of the respective grid infrastructure. However, based on the statistical distribution of VoLGs in the two analysed voltage levels, also a few general conclusions can be drawn: Firstly, we specified the ratio of the economic importance of the medium- to the low voltage grid, expressed in a more than three times higher median VoLG of the medium voltage grid compared to the median VoLG of the low voltage grid. Secondly, comparing the statistical distribution of VoLLs to the distribution of VoLGs showed that the interregional heterogeneity of VoLGs is substantially higher on both voltage levels compared to the heterogeneity of VoLLs. In particular the medium voltage grid is characterised by large variations in the VoLG. Domains of comparably high VoLG are especially associated with those DGOs, characterised by a high ratio of electricity consumption to domain area, which is often found in rather densely populated domains. Apparently, in these domains, less infrastructure is needed to supply a comparably high amount of electricity to consumers. Examples of these domains are most operators in charge of geographically rather small network domains and few larger operators in the South-West and West of Germany. Thirdly, it became clear, that the uncertainty attached to operator- and voltage level-specific VoLGs, which resulted from the partly ambiguous mapping of sectoral electricity consumption from county- to operator- and voltage level-resolution, is especially pronounced with respect to the medium voltage level. Nonetheless, in many cases a comparison between operators still provides meaningful

[23]The IQR of VoLLs is 15.7% of median low voltage VoLL and 55.5% of median medium voltage VoLL, whereas the IQR is 76% of median low voltage VoLG and 109% of median medium voltage VoLG.

insights, since (i) differences between the operator-specific mean VoLGs in the medium voltage grid in many cases exceed the uncertainty attached to the individual VoLGs and (ii) having in mind, that the uncertainty measure introduced was based on the maximum possible deviation from the determined mean value.

In a general sense, these outcomes contribute to an economic assessment of all events potentially triggering electricity outages within the distribution grids: In domains with high relative economic value generation of the grid infrastructure, there is – from an economic perspective – an argument to opt for a relatively safer design of the infrastructure compared to domains with less relative economic importance of the infrastructure (when outage risks are uniform). Hence, this study's results can contribute to the design planning of expansions in the distribution grid with respect to resilience and redundancy, and can provide guidance with respect to decision making on maintenance and retrofitting measures. Regulators that currently control expenditures by DGOs primarily for efficiency (Welle and Zwaan, 2007; Ward, 2013) may consider whether operators have proper incentives to invest such that the relative economic importance is incorporated in their decision making. With respect to climate change induced physical risks on the distribution networks, this study's methodology provides a relevant tool to assess climate change induced economic risks on the electricity distribution networks and strengthens and supports the scientific basis for climate services to the electricity distribution sector.

For the correct interpretation of this study's findings, the following issues should be taken into consideration. Firstly, this study cannot answer the question whether the current resilience and redundancy of the grid well reflects the economic risks it is exposed to. Secondly, one needs to be aware of the limitations arising from the assumptions inherent in the production function- and household income approach, as discussed in subsection 2.1. Thirdly, it has to be stressed that an economic evaluation can only be part of an overall analysis which should certainly incorporate ethical and political considerations, such as the potential implications, when areas of less relative economic importance whose inhabitants already feel socially and economically disadvantaged are treated differently (in terms of outage security of the grid) from those areas of high economic importance. Finally, we believe that this paper's results cannot replace a more regionally detailed analysis, since within the domain of an individual DGO, the relative economic importance of the operational reliability of each infrastructure unit may again vary significantly. Therefore, an assessment of the economic importance for each individual infrastructure unit may guide decision making in a more precise manner. However, an analysis of this kind would require information on VoLLs and structural grid data on an extremely high spatial resolution, which are either not publicly available or not collected.

This analysis provides a sound starting point to economically assess differences in the relative importance of the distribution grid infrastructure and strengthens the scientific basis for climate services to the electricity distribution sector. We do not expect the observed heterogeneity of relative economic importance of the distribution grid infrastructure to be unique for Germany. Hence, contingent upon data availability, a transfer of the suggested methodology to other countries can help identify differences in the relative economic importance of electricity distribution infrastructures.

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