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Reliability with interdependent suppliers[☆]

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ABSTRACT

We study reliability and the role of interdependent suppliers with reference to electricity systems. Individual availability of supply is uncertain and may exhibit dependencies with other suppliers as well as with the stochastic demand. Aiming at a comprehensive and consistent reliability assessment, we first investigate the system as a whole, and then derive a general solution for an individual supplier's contribution. Implicitly, we identify changing returns to scale, gains of diversification, and non-additivity. As these properties are often undesirable, e.g., for the purpose of accounting or in specific auction formats, we build on concepts from cooperative game theory to provide the Shapley value as the unique consistent reliability allocation rule. We then illustrate practical relevance and applicability of our approach for the case of wind power contributing to the reliability of Germany's electricity system, and discuss how today's reliability mechanisms may be improved by considering interdependencies between suppliers.

1. Introduction

Reliability is a key concern in virtually any supply chain. This is true, in particular, for electricity systems where blackouts can cause enormous costs. Hence, electricity system operators (SOs) must be able to evaluate overall system reliability as well as the contribution of individual suppliers. This is important for consistent system assessments, but also for the purpose of optimal capacity planning, e.g., when deciding whether or not to include a new generator in the portfolio. Moreover, knowing the value of individual generators for overall system reliability should also be the basis when deciding on the allocation of scarce resources (such as maintenance capacities), or when remunerating individual suppliers for their specific contribution, e.g., in so-called capacity mechanisms.[1]

For conventional power plants, determining their contribution is relatively easy, due to the fact that their availabilities are largely independent. For variable renewable energies (VRE), however, this is far more complex: stochastic interdependencies between different sites must clearly be taken into account, especially when the shares of wind and solar power are rising. A wind generator at site *A* with little wind (and therefore, individually rather unreliable) may be much more valuable for the system than a generator at site *B* with more wind – if the portfolio already comprises many generators at *B*, and if there is a negative correlation of wind between *A* and *B*.

The key challenge in systems with high shares of wind and solar power therefore arises in accounting for the stochastic interdependencies which imply that a separate evaluation of suppliers is no longer possible. Hence, in this paper, we provide a general solution for evaluating the contribution of stochastic (electricity) suppliers to overall system reliability in terms of generation capacity adequacy, allowing for arbitrary stochastic relations between suppliers as well as between suppliers and demand. We show that, in general, individual contributions are non-additive, show non-constant returns to scale, and exhibit gains from diversification. Noticing that these properties are often undesirable, e.g., for the purpose of (reliability) accounting or in specific auction formats,[2] we build on concepts and findings from cooperative game theory to provide the Shapley value as the unique rule to consistently

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[1] In a capacity mechanism, the SO determines a certain requirement for firm capacity, while the requested amount is often procured in an auction. In order to participate, generators have to pre-qualify, i.e., one needs to determine how much of their installed capacity is firm and can be offered in the auction, based on the technical properties of the supplier.

[2] For instance, the performance of a descending clock auction – which is the typically applied auction format in capacity markets for electricity – strongly relies on the assumption that individual values are additive.

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allocate reliability contributions to individual interdependent suppliers.

Subsequent to our theoretical analysis, we investigate an empirical case study to demonstrate applicability and practical relevance of our theoretical findings. Due to its high level of penetration, we deal with wind power in the German electricity system. Our results clearly illustrate that individual average availabilities and true contributions can differ significantly, and that the Shapley value is indeed a meaningful tool for evaluating complex interdependent supply portfolios.

In the last part of our paper, we discuss important implications of our findings for capacity planning problems where individual suppliers need to be evaluated, incentivized and remunerated. We find that in sharp contrast to our results, practice has often been neglecting interdependencies of suppliers. Especially, capacity mechanisms worldwide use a wide range of different prequalification rules (typically depicted as x% of name plate capacity). In Spain, wind and solar are prequalified with zero value – which clearly underestimates their contribution. In the UK mechanism, an average value is attributed by class of technology (coal, gas, wind). In the PJM capacity auction, each generator is prequalified individually, based on its average availability. It is obvious that all of these procedures do not reflect the true contribution of individual sites to reliability since they neglect the interdependencies with other suppliers in the portfolio. Underpinned by our theoretical and empirical analysis, we conclude that state-of-the-art approaches to manage reliability in large and complex systems may be substantially improved based on the findings of our paper.

The remainder of the paper is organized as follows: After discussing the related literature in Section 2, Section 3 presents the theoretical framework and our main theoretical results for how to evaluate individual contributions to reliability. In Section 4 we provide an empirical case study to illustrate our findings based on realistic data for wind power in Germany. Section 5 discusses important implications for capacity planning problems. Section 6 concludes.

2. Related literature

Power system reliability has been investigated extensively from various angles. First approaches to determine the *technical* sufficiency of generation capacities to meet expected load levels (i.e., generation adequacy) have been presented by Garver (1966) and Billinton (1970). Initially developed for conventional power plants, later work has been transferring these measures to the case of variable renewable energies. Especially, several studies assessed the contribution of specific renewable energy technologies (such as wind and solar) to reliability of supply, often referred to as capacity credit or capacity value (for recent surveys, see, e.g., Amelin (2009) or Keane et al. (2011)). While this stream of literature typically deals with the problem numerically, our paper contributes a comprehensive and consistent analytical framework to solve for the contribution of individual suppliers to reliability of supply.

Our paper also relates to the *economic* analysis of power system reliability. The (in)ability and potential failures of power markets to provide reliability as a market outcome were studied, e.g., by Bunn and Oliveira (2008), Joskow (2008) or Cramton, Ockenfels, and Stoft (2013). On a firm level, investment incentives in the (strategic) capacity expansion planning problem induced by specific market designs were investigated by Murphy and Smeers (2005), Zöttl (2010), Ehrenmann and Smeers (2011), or Golari, Fan, and Jin (2017), for instance. In contrast to these papers, we depict important implications of the *technical* contribution of individual suppliers for the *economic* design of regulatory interventions and market mechanisms to ensure reliability of supply. Specifically, we complement existing research that has disregarded the specific role of stochastic and interdependent suppliers. Our paper fills this gap by suggesting suitable approaches to incorporate those suppliers into reliability-related mechanisms in order to ensure economically efficient outcomes.

In addition to the literature on reliability in power systems, our paper is also related to the more general context of supply chain management. First, we build on literature on supply chain reliability and the problem of strategic sourcing of a homogenous good from multiple suppliers. Supply disruptions (i.e., binomial distributions) with multiple suppliers have been studied by Parlar and Perry (1996), Gürler and Parlar (1997), Li, Xu, and Hayya (2004) and Tomlin (2006), however, without considering stochastic dependencies among the suppliers. As a natural extension, later papers allow for statistical dependencies (i.e., Babich, Burnetas, & Ritchken, 2007; Hu & Kostamis, 2015; Li, Wang, & Cheng, 2010; Wagner, Bode, & Koziol, 2009). Continuous distributions of the suppliers' uncertainties – as used in our paper – were presented by Dada, Petruzzi, and Schwarz (2007) and Masih-Tehrani, Xu, Kumara, and Li (2011). Compared to these references, our paper deviates in several important aspects: Instead of analyzing the costs of supply chain reliability under exogenous prices, we take a different perspective on the problem by endogenously determining the individual supplier's value for supply chain reliability. This allows us to disentangle the role of interdependent suppliers, while considering arbitrary and interdependent distributions of (un)availability and demand. In addition, we present a novel solution based on concepts from cooperative game theory to derive a consistent reliability allocation, and discuss important implications for capacity planning in large and complex supply chains. Second, we also build on findings derived in the context of efficient coordination and investment incentives in vertical supply chains. Specifically – similar to Inderst and Wey (2003), Brandenburger and Stuart (2007) and Feess and Thun (2014) – we acknowledge and explicitly account for the need to reflect individual suppliers' marginal contributions to the system to reach efficient outcomes. This prerequisite naturally gives rise to the Shapley value as an allocation rule.

3. Reliability model

3.1. System reliability

We consider a one-period system $\mathcal{S}$ consisting of numerous suppliers (e.g., wind generators) delivering a homogenous good (electricity). The set of suppliers is denoted by N, and suppliers are characterized by their joint stochastic availability of supply capacity C.[3] Demand D is also assumed stochastic. Due to considering only one period without additional backup (such as, e.g., storage, emergency service, etc.), supply shortages occur whenever C is unable to cover D. Note that we develop our reliability model based upon one period only to ensure analytical tractability and comprehensibility. However, the problem can easily be extended to include variations in the involved variables across multiple periods, such as time-variant characteristics of the demand distribution, for instance. To this end, each variable would be assigned with a time index t, and the shortage probability be summed up over all t to represent expectations across the considered time frame. This extension is presented in Section 4.1 to reflect criteria commonly applied in power systems, i.e., reliability as a probability of shortages

[3] Here and in the following – unless indicated differently – capital letters are used for random variables.