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A generic framework for power system flexibility analysis using cooperative game theory

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HIGHLIGHTS

- Alternative method for flexibility analyses using Shapley Value.
- The method is demonstrated with a multinational offshore grid case study.
- Demand for flexibility options are identified by countries and technology.
- Implicitly accounting for uncertainty in lead time and innovation.
- Generate insights for multinational policy designs or investment analyses.

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ABSTRACT

Electricity grid infrastructures provides valuable flexibility in power systems with high shares of variable supply due to its ability to distribute low-cost supply to load centers (spatial), in addition to interlinking a variety of supply and demand characteristics that potentially offset each others negative impact on system balance (temporal). In this paper, we present a framework to investigate the benefits of alternative flexibility providers, such as fast-ramping gas turbines, hydropower and demand side management, by using a generation and transmission capacity expansion planning model. We demonstrate our findings with a multinational case study of the North Sea Offshore Grid with an infrastructure typology from year 2016 and operational data for year 2030 – considering a range of renewable capacity levels spanning from 0% to 100%. First, we show how different flexibility providers are allocated geographically by the model. Second, operational cost savings are quantified per incremental unit of flexible capacity. Finally, we present a way to rank different flexibility providers by considering their marginal contribution to aggregate cost savings, reduced CO_2 emissions, and increased utilization of renewable energy sources in the system. The Shapley Value from cooperative game theory allows us to assess the latter benefits accounting for all possible sequences of technology deployment, in contrast to traditional approaches. The presented framework could help to gain insights for energy policy designs or risk assessments.

1. Introduction

The European power system is exposed to large-scale integration of renewables the coming decades [1], demanding more flexibility in order to distribute, consume, or store variable levels of power feed-in [2]. An adequate grid infrastructure can contribute with spatial flexibility by distributing power surpluses over larger geographical areas, which in turn connects the variable generation to distant load centers and potential energy storage (temporal flexibility) reducing system imbalances [3]. Hence, increased flexibility in both space (spatial) and time (temporal) could be achieved with grid expansion. In addition to a more efficient use of clean resources and decreased green house gas (GHG) emissions, this is the reason why the North Sea Offshore Grid (NSOG) has been identified by the EU Commission as one of the strategic trans-European energy infrastructure priorities in the EU Regulation No 347/2013. Potentially serving the twofold purpose of integrating offshore wind power generation while, at the same time, facilitating for increased cross-border trade.

Spatial and temporal flexibility are a key elements to maintain security of supply and ensuring cost-efficient utilization of variable renewable energy sources (VRES) feed-in [4]. More electricity grid is needed in order to reach future energy- and climate targets and ENTSO-

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E estimates €150bn worth of pan-European energy infrastructure investments the next decade, with current supply and demand projections. A large share these investments comprise multinational electricity grid expansion [5]. One of the main challenges when it comes to planning for such investments is the geographical span that needs to be considered [6]. That is, by connecting larger geographical areas through an infrastructure means that multivariate characteristics from multiple countries, with their respective supply- and demand mix, has to be accounted for in order to capture underlying values of larger system dynamics. For instance, the synergy value of VRES, such as offshore wind in the coastal areas of Great Britain, and energy storage facilities, such as hydropower located in the Norwegian mountains [7].

The geographical span does not only affect the computational complexity in long-term planning models, but it also induces tighter market integration between countries. When building a new, or expanding an old, transmission corridor – price effects will occur at adjacent connection points [8]. These adjacent points are, in our case, countries that experience a change in welfare, i.e. consumer surplus and producer surplus. In turn, this might lead to impact on neighbouring regions or countries as shown in [9] focusing on distributional effects of transmission expansion. In Egerer et al. [10] they study the welfare implications of grid expansion in the NSOG. Other similar studies, but in context of renewable portfolio standards, includes an assessment of the Western Electricity Coordinating Council (WECC) in the US [11].

Evaluating the need for, and impact of, flexibility options is thus a complex task considering the size and dynamics of a power system, and its economic implications. Moreover, as technology matures and costs decreases, other flexibility options might evolve as cost competitive compared with grid expansion. Hence, there is an uncertainty element that should be incorporated when assessing the added value of flexibility sources over a long economic lifetime [12]. For instance, the deployment sequence of different flexibility providers might have an economic impact on previous, and future, deployments of other technologies.

This paper presents a generic framework for geographical- and economic evaluation of flexibility options. We use a generation and transmission expansion planning (GTEP) model and leverage methods from cooperative game theory [13] in order to cope with the aforementioned context. More precisely, we exploit the properties of The Shapley Value (SV) [14] in order to account for different deployment sequences and, consequently, use this information to assess the contribution from each flexibility provider to system benefits. To this end, we are able to somewhat account for future uncertainty in, e.g., innovation and deployment sequence without the need of sophisticated, stochastic programming tools. However, we do not claim that the presented approach is a substitute for the latter – rather a complement. We demonstrate the added value in terms of more insights to the problem at hand.

The remaining parts of this paper is structured as follows. Section 2 overviews existing literature on how to quantify the need for system flexibility and its contributions on system level, extended with recent work on cooperative game theory for power system applications. Section 3 presents the GTEP expansion planning model, case study setup, and a brief introduction on how the SV is calculated. Finally, results from the NSOG case study is presented in Section 4 followed by a conclusion with recommendations for future work in Section 5.

2. Literature

This section overviews existing literature and power system flexibility analyses, with a particular focus on long-term planning models that are used for GTEP. Together with a review on relevant applications of cooperative game theory, we derive our contributions in the end of the section.

2.1. Long-term planning models and flexibility analysis

As already mentioned in the introduction, novel GTEP models has to incorporate a significant level of details in order to account for current and future market characteristics. At the same time, they have to include larger geographical areas as discussed in prominent TEP reviews by Lumbreras and Ramos [6] and, with a focus on multinational offshore grids like the NSOG by Gorenstein Dedecca and Hakvoort [15]. It has been shown that there is an underlying value in capturing system dynamics over larger areas due to smoothing effects [16]. For instance, by aggregating VRES generation over a larger geographical area the net feed-in on system level tends to be smoother than for smaller areas due to weather variations. This effect could offset some need for flexibility, at least temporal, whereas spatial flexibility has to be in place in order to link those interdependencies.

Moreover, the material price impact of lumpy grid investments creates incentives for generators to respond with changes in their generation mix due to potential price arbitrage [8], meaning that cost-efficient equilibria are not met if not considering both transmission and generation expansion due to its synergies on cost recovery [17]. Other challenges in the GTEP literature include, but is not limited to, incorporation of uncertainty [18], representation of loop flows [19], distributed generation, demand side management, detailed energy storage handling, and FACTS devices [20]. The main challenge is that operational details comes with an expense of the larger and more complex optimization programs, consequently leading to mathematical difficulties such as non-convexity and intractable models.

Flexibility is referred to as the key term of the future by Auer and Haas [2] and has received increasing attention over the last years. One occurring topic is the mapping of different metrics to quantify the level of flexibility in a power system [21]. High-level metrics such as peak demand, regional grid strength, interconnections with other areas, the number of power markets, and the generation mix are identified as the most important ones [4]. Subsequently, this could be broken down to individual flexibility providers such as demand side management (DSM), fast-ramping generators, or energy storage. A comprehensive review of different technologies and strategies is presented in [3].

The most prominent contributor to a cost-efficient and reliable development of the power system is grid expansion. This has been demonstrated for the European case by Fürsch et al. [22]. Moreover, Huber et al. [23] has investigated short-term aspects of flexibility on an hourly scale with different levels of VRES and geographical span, concluding that flexibility needs are smaller for interconnected, transnational power systems. The same conception of grid infrastructures being a significant contributor to the availability of flexibility, both in temporal and spatial form, is shown by Lannoye et al. [24] using Insufficient Ramping Resource Expectation (IRRE) and the Periods of Flexibility Deficit (PFD) as explanatory metrics. However, uncertainty is left out of scope in the aforementioned literature.

Konstantelos and Strbac [12] acknowledge that transmission grid investments are important for the future power system development, but questions its competitive edge compared with other flexible network technologies. They demonstrate the value of incorporating multiple flexibility options where costly grid reinforcements could be avoided, and that models ignoring uncertainty could systematically undervalue benefits of flexibility options. The approach of considering multiple options under uncertainty has reached a consensus as one of the most frequent shortcomings in the existing literature [25]. The latter review paper highlights learning curves and innovation, where a majority of planning models, especially static ones, might yield inefficient lock-in of established technology options. In this paper, we will to some extent account for the reviewed shortcomings, by utilizing a relatively simple approach compared to using, e.g., a multi-stage stochastic program or robust optimization.