Essays on Wind Energy Economics and Policy

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Abstract

This cumulative dissertation presents six research articles, all of which have been accepted and published in peer-reviewed journals and conference proceedings. Special attention is paid to renewable energy finance and policy in the wind energy sector. In the domain of renewable energy auctions, a risk-constrained marginal cost model is derived that enhances strategic bidding optimization. The research results and findings enable project developers to quantify competitive and risk-adequate auction bids. In the domain of end-of-life of wind turbines, economic and spatial analyses are combined to provide methodological support for turbine operators and policy-makers. The developed decision support system is capable to determine whether lifetime extension, repowering, or decommissioning is the optimal end-of-funding strategy for entire wind fleets. All research articles of this dissertation place a significant emphasis on practical applications and address real-world challenges of different stakeholders in the field of wind energy.

Keywords: Wind Energy · Energy Economics · Renewable Energy Auctions · Energy Policy · Spatial Analysis · Decision Support Systems

Management Summary

Renewable energies, like solar and wind power, play a key role in mitigating climate change. In this cumulative dissertation, research articles that have a strong practical focus and address identified real-world challenges for wind energy are summarized and discussed. The six research articles are published in peer-reviewed academic journals and conference proceedings. The research articles address pre-operational as well as post-operational challenges for different stakeholders of wind energy turbines.

As well-informed decisions will likely foster the deployment of renewable energies, the overall research motivation is to develop comprehensive decision support for wind energy stakeholders such as project developers, turbine operators and policy-makers. The conducted research and related publications are divided into two research domains as shown in Table 1. By deriving a marginal cost model, the first research domain contributes to competitive bidding in renewable energy auctions and provides decision support for offshore wind turbine manufacturers in the design of turbine substructures. The second research domain deals with end-of-life issues of wind turbines and provides decision support for stakeholders whether to extend the lifetime, repower or decommission. Here, entire wind fleets are analyzed to derive policy implications.

The conducted research follows the design science research (DSR) approach in order to maintain a transparent and rigorous research process. By means of technological artifacts instantiated as a decision support systems (DSS), the identified challenges and corresponding research questions are addressed. The dissertation concludes with overall contributions and limitations of the conducted research. The

	Chapter	Research Article
Marginal Cost and Competitive Bidding in Renewable Energy Auctions	2.1	Enhancing Strategic Bidding Optimization for Renewable Energy Auctions: A Risk-Adequate Marginal Cost Model
	2.2	Influence of structural design variations on economic viability of offshore wind turbines: An interdisciplinary analysis
	2.3	Competitive and risk-adequate auction bids for onshore wind projects in Germany
End-of-Life Decision Making for Wind Turbines: A Macro-Scale Perspective	3.1	Lifetime Extension, Repowering or Decommissioning? Decision Support for Operators of Ageing Wind Turbines
	3.2	A Real Options Approach to Determine the Optimal Choice Between Lifetime Extension and Repowering of Wind Turbines
	3.3	Hidden repowering potential of non-repowerable onshore wind sites in Germany

Table 1: Research domains with corresponding research articles

following briefly summarizes the two research domains and outlines how the research articles methodically build upon each other and how the research progressed over time.

Marginal Cost and Competitive Bidding in Renewable Energy Auctions

The shift in policymaking towards market-based support mechanisms, particularly auctions, represents a pivotal change in the landscape of renewable energy funding (Winkler et al., 2018). This transition, driven by the need to mitigate costly market distortions and reduce subsidy expenses (Huntington et al., 2017), places a strong emphasis on competitive pricing and financial viability in the renewable energy sector. Auctions, by introducing competitive dynamics among project developers, aim to prevent the overcompensation and to grant funding to only the most financially viable projects. This new competitive environment greatly decreases profit margins del Río and Linares (2014a); Abdmouleh et al. (2015); González and Lacal-Arántegui (2016) and leaves no room for valuation errors in bid price quantification. Overestimating bid prices can result in the exclusion from funding opportunities, while underestimating can lead to unprofitable ventures.

Current research (Anatolitis and Welisch, 2017a; Voss and Madlener, 2017a) provides models for calculating strategic bids in auctions, considering factors such as competitive dynamics and the presence of several bidding rounds. The key to determine bidding strategies in renewable energy auctions lies in accurately quantifying the marginal cost. This cost represents the lowest price per unit of electricity at which a project is economically viable at an acceptable risk level. Within auction environments, this initial determination is vital as it influences a project developer's capacity to create bids that are both competitive and financially viable.

The first research article (Stetter et al., 2019) of this dissertation enhances strategic bidding optimization by deriving a risk-adequate marginal cost model. First, it addresses the shortcoming of traditional discounted cash flow models of not adequately accounting for the project-specific risks and uncertainties inherent in renewable energy investments. Second, a risk-constrained optimization minimizes the required sales price per unit of electricity while considering the investment criteria of equity and debt investors. Equity investors deem the investment criteria satisfied when the adjusted present value (APV) is non-negative as shown in Figure 1, signaling the project's financial feasibility. As illustrated in Figure 2, debt investors require a specific target of the project's debt service cover ratio (DSCR) to ensure the project's capability to fulfill its debt commitments. The authors illustrate the applicability of the risk-adequate marginal cost model through a case study on an onshore wind farm in Lower Saxony, Germany. The study demonstrates that substructure designs with enhanced durability and longer lifespans, despite their higher initial capital expenditures, prove to be more competitive over the long term, as indicated by their lower marginal cost compared to less expensive

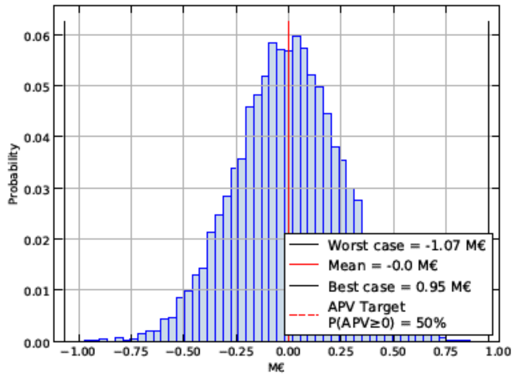

Figure 1: Histogram of APV after optimization (Stetter et al., 2019, p. 221)

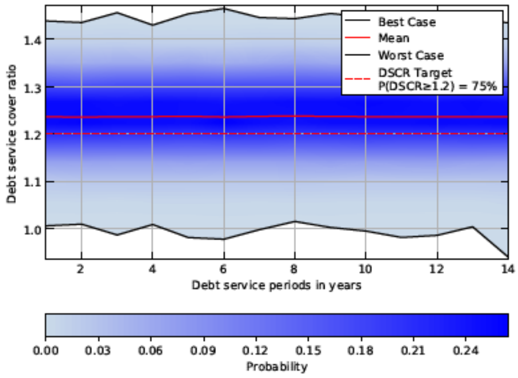

Figure 2: DSCR after optimization (Stetter et al., 2019, p. 222)

designs with potentially shorter operational durations.

Building on the preliminary model derivation presented in a conference proceeding, the second research article (Hübler et al., 2020) of this dissertation demonstrates the applicability of the risk-adequate marginal cost model in an interdisciplinary analysis in the domain of offshore wind energy. Expanding on the initial findings, this journal publication offers a comprehensive derivation and more detailed presentation of the marginal cost model. Offshore wind turbine substructures account for nearly 20% of a wind farm's capital expenditures, highlighting a key opportunity for cost optimization and enhancing the competitiveness of offshore wind energy projects. By integrating an aero-elastic wind turbine model with the marginal cost model, the economic outcomes of design variations for substructures of offshore wind turbines are examined. The probability density function (PDF) of the APV fore different substructure designs are shown in Figure 3 and Figure 4 and illustrate that more durable designs are more economically feasible despite their higher costs. Through this analysis and the presented interdisciplinary modeling approach, decision support for wind turbine manufacturers in developing the most competitive designs for offshore wind turbine substructures is provided.

The contributions of this dissertation to methodological support for renewable energy auctions closes with a third research article (Stetter et al., 2020b) within

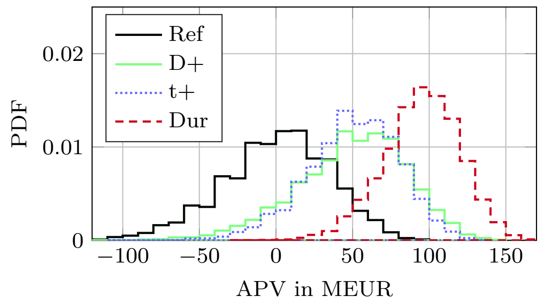

Figure 3: APV PDF for more durable substructure designs (Hübler et al., 2020, p. 1357)

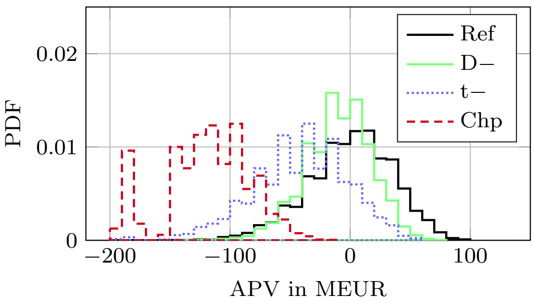

Figure 4: APV PDF for cheaper substructure designs (Hübler et al., 2020, p. 1357)

this domain. This research article builds upon the foundations laid in Stetter et al. (2019) and Hübler et al. (2020) and demonstrates the integrating of the risk-adequate marginal cost model into a strategic bidding optimization. With strategic bidding, one can estimate an additional premium beyond the marginal cost that should be included in the bid price, aimed at optimizing the project's expected profit while ensuring competitiveness in the auction process. By integrating the two approaches, project developers are able to derive risk-adequate and competitive auction bids that fulfill the investment criteria of all project stakeholders. The practical application of this integrative modeling approach was showcased in a case study, simulating bidding strategies for a German project developer involved in an onshore wind farm project.

End-of-Life Decision Making for Wind Turbines: A Macro-Scale Perspective

By 2025, a significant portion of Germany's wind energy turbines, representing over a third of its installed capacity, will reach end of their feed-in tariff funding (EEG, 2017), affecting more than 13,000 turbines (16.4 GW). This imminent transition necessitates crucial decisions for operators regarding the future of aging wind turbines, with the options of extending their operational life at prevailing market rates or through power purchase agreements (PPA), repowering with more efficient turbine models, or opting for decommissioning. While lifetime extension presents a possible option given technically viability, future electricity prices are subject to uncertainties which significantly impacts its economic viability. On the other hand, repowering presents an opportunity for enhanced efficiency and energy output but is significantly constrained by stringent distance regulations, particularly the spatial planning regulations that mandate minimum distances between turbines and residential areas. Therefore, deriving optimal end-of-funding strategies is a complex and critical task for wind turbine operators, manufacturers and policy-makers alike.

Existing literature predominantly examines the topics of lifetime extension (Ziegler et al., 2018a; Rubert et al., 2018a, 2016) and repowering (Serri et al., 2018; Villena-Ruiz et al., 2018; Colmenar-Santos et al., 2015a) as separate subjects, often without considering a macro-scale perspective. Additionally, while studies like those by Stede and May (2020) delve into the challenges posed by restrictive distance regulations on onshore wind energy deployment in Germany, they tend to focus on specific regions and do not utilize detailed vector data, which is crucial for a precise evaluation of repowering opportunities.

The first research article (Piel et al., 2019b) in this domain presents a DSS to assess the potential for lifetime extension and repowering of wind turbines on a macro scale and therefore enables operators and other stakeholders to derive optimal end-of-funding strategies. Utilizing a geographic information systems (GIS), the study initially evaluates the feasibility of repowering at any given turbine site based on spatial and regulatory constraints. Subsequently, the economic viability of repowering and lifetime extension is compared by employing a differential investment analysis to maximize the net present value (NPV) of each strategy. A case study in Lower Saxony illustrates the applicability of the DSS that combines resource, spatial and economic analyses. The results of the case study are illustrated in Figure 5 and show that the optimal end-of-funding strategy for one third of the wind turbines is immediate repowering. Another third is recommended for operation extension prior to repowering, and the remainder are best suited for either continued operation without repowering or decommissioning.

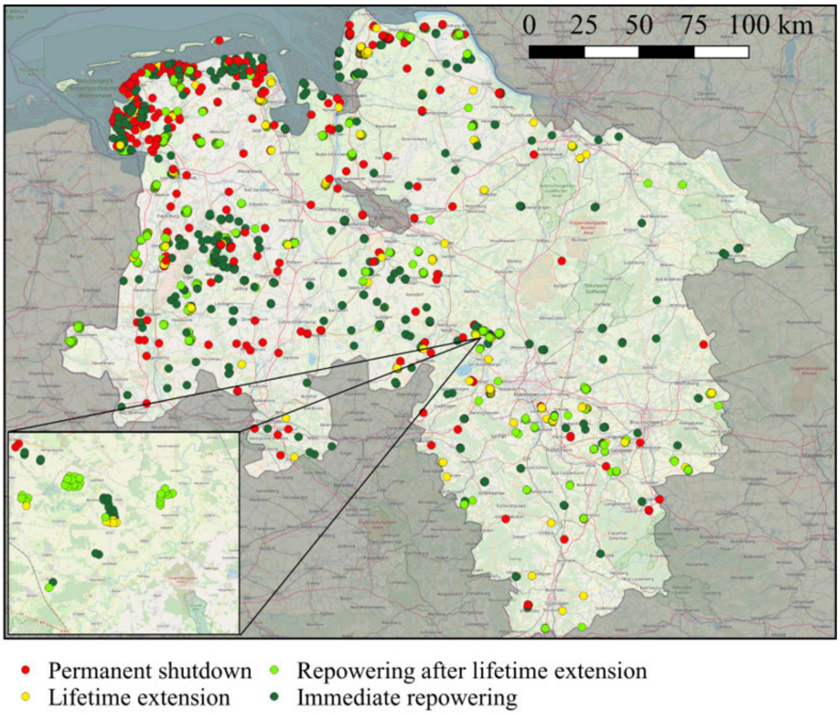

Figure 5: Optimal end-of-funding strategies for wind turbines in Lower Saxony (Piel et al., 2019b, p. 8)

Building upon the holistic evaluation of optimal end-of-funding strategies from the first research article, the second research article (Stetter et al., 2020a) in this domain focuses on the economic viability analysis and enhances the methodology by considering uncertainties. The evaluation of repowering or extending the life of wind turbines, is characterized by the irreversibility of capital investments, uncertainty in future revenues, and the timing flexibility of investments. By integrating the net present repowering value (NPRV) (Silvosa et al., 2013) and a real options approach (Himpler and Madlener, 2014a), methodological support to consider uncertainties and the managerial flexibility inherent in repowering projects is provided in the context of optimal end-of-funding strategies. This methodology is validated through a case study involving ten wind turbines in Lower Saxony, Germany, focusing on determining the optimal strategy for end-of-funding scenarios. Here, the flexibility to postpone investment decisions in face of uncertainties is exemplified by simulating uncertain future electricity prices.

The exploration of macro-level end-of-life issues for wind turbines in this dissertation closes with a third research article (Stetter et al., 2020b), contributing policy implications of repowering potentials at the individual turbine level in Germany. A GIS is presented that leverages high-granularity vector data to accurately assess repowering opportunities, especially in light of spatial planning constraints mandating minimum distances between wind turbines and residential areas. The study discusses the potential of established wind turbine sites, which have the necessary infrastructure and local acceptance, as prime candidates for repowering. The research findings for each federal state are presented in Figure 6 and show a great potential of equipping non-repowerable but well-established locations with new and more efficient turbine models at the same height. For the entire German

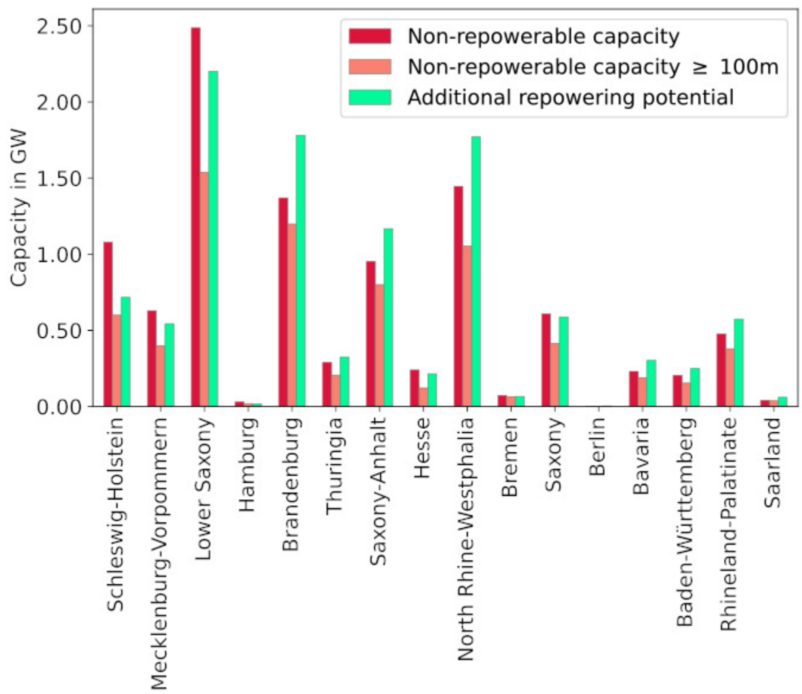

Figure 6: Non-repowerable capacity and the derived additional repowering potential (Stetter et al., 2022, p. 7)

wind fleet this strategy features the potential of doubling the capacity compared to sites already classified repowerable. Specific policy adjustments to realize this potential are suggested and discussed.