Contributions of Information Systems Research to Decision Support for Wind Market Players

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I. Abstract

The mitigation of climate change through the transition toward sustainable and efficient energy systems based on renewable energy technologies is one of the greatest challenges of the 21st century pursued by an ever-growing number of individuals, organizations, and societies in large. The extensive financial support of many nations for renewable energies has led to a rapid global spread of these technologies in the last two decades. Nowadays, as renewable energy technologies are maturing, governments tend to implement more market-based support mechanisms in order to scale back financial support, which poses new challenges for all market players. Consequently, in a consolidating market environment, only those players can establish themselves in the market, who have the right information at the right time in order to make the best possible decisions on newly emerging issues. In this context, this thesis demonstrates the high potential of information systems (IS) research on decision support systems (DSS) in making solution-oriented and impactful contributions to affected renewable energy stakeholders by improving the decision-making process through aggregated information. Six consecutive thematic topics are presented and discussed based on several research articles, each addressing a specific challenge of different renewable energy stakeholders by means of quantitative design science research (DSR) on DSS. The thematic spectrum ranges from micro-level challenges of individual renewable energy operators to macro-level challenges of policy-makers. A strong focus is placed on renewable energy finance and policy topics in the field of the wind energy sector. Findings indicate that the role of appropriate and customized DSS is becoming increasingly important for all market players, due to the constantly growing diversity of information and amount of data available in the rapidly digitalizing renewable energy sector. They further point to the strength and necessity of IS research with regard to its integrative function between other research areas and how this property could be used in order to respond to the need for more practical support for decision-makers concerned with environmental and sustainability issues.

Keywords: Renewable Energy, Wind Energy, Information Systems Research, Decision Support, Simulation, Optimization, Design Science

Zusammenfassung

Die Abschwächung des Klimawandels durch den Übergang zu nachhaltigen und effizienten Energiesystemen auf Grundlage Erneuerbarer Energien (EE) ist eine der größten Herausforderungen des 21. Jahrhunderts, der eine ständig wachsende Anzahl von Organisationen und Gesellschaften nachgeht. Die umfangreiche finanzielle Förderung vieler Nationen für EE hat in den vergangenen zwei Jahrzehnten weltweit zu einer großen Verbreitung dieser Technologien geführt. Da EE seither immer wettbewerbsfähiger werden, neigen politische Entscheidungsträger vieler Nationen heutzutage dazu, zunehmend marktbasierte Fördermechanismen einzuführen, um die finanzielle Förderung dauerhaft zu reduzieren, wodurch neue Herausforderungen für alle Marktteilnehmer entstehen. In einem sich konsolidierenden Marktumfeld können sich daher nur diejenigen Akteure langfristig am Markt etablieren, die über die richtigen Informationen zur richtigen Zeit verfügen, um bei neu auftretenden Fragestellungen stets die bestmöglichen Entscheidungen treffen zu können. In diesem Zusammenhang zeigt die vorliegende kumulative Dissertation das hohe Potenzial der IS Forschung im Bereich von Entscheidungsunterstützungssystemen (EUS), lösungsorientierte und wirkungsvolle Beiträge an EE-Stakeholder zu leisten, indem sie deren Entscheidungsprozesse durch aggregierte Informationen verbessert. Sechs aufeinander folgende thematische Abschnitte werden auf Grundlage von Forschungsartikeln vorgestellt und diskutiert und befassen sich jeweils mit der Lösung einer spezifischen Herausforderung verschiedener Stakeholder mittels quantitativer DSR Methoden. Das thematische Spektrum reicht von mikroskaligen Herausforderungen einzelner Betreiber bis hin zu makroskaligen Herausforderungen politischer Entscheidungsträger. Ein besonderer Schwerpunkt liegt auf dem Windenergiemarkt im Bereich der Finanzierung und Politik. Die Ergebnisse deuten darauf hin, dass die Rolle von EUS für alle Marktteilnehmer aufgrund der ständig wachsenden Diversität an Informationen und Datenmengen im schnell digitalisierenden EE-Sektor immer wichtiger wird. Sie weisen ferner auf die Stärke und Notwendigkeit der IS Forschung im Hinblick auf ihre integrative Funktion zwischen anderen Forschungsbereichen hin und zeigen auf, wie diese Eigenschaft eingesetzt werden kann, um dem Bedarf an praktischer Unterstützung für Entscheidungsträger, die sich mit Umwelt- und Nachhaltigkeitsfragen befassen, zu begegnen.

II. Management Summary

Mitigating climate change through energy transition to renewable energy technologies is one of the greatest challenges of the 21st century. In this regard, wind and solar energy plants in particular are an important pillar of a sustainable energy mix in most regions. Consequently, many governments have promoted the rise of wind and solar markets through extensive financial support mechanisms with low market integration in the past to allow these technologies to compete with conventional power generation. This has led to rapid increases in efficiency and cost reductions in these technologies due to strong market growth and high competition between manufacturers.

Today, wind and solar energy account for a significant proportion of global electricity generation and the corresponding markets have become important drivers of job and value creation in many regions. As markets mature, governments around the world tend to use more market-based support mechanisms to determine financial support through market mechanisms and reduce subsidy costs. The resulting reduction in profit margins and increase in sensitivity to risk and uncertainty lead to extensive market consolidations. In the long term, only those players can establish themselves in the market who have the right answers to the newly emerging challenges in a changing market environment. Hence, it is highly essential for all market players to have the right information at the right time in order to make the best possible decisions regarding these challenges.

In this context, information systems (IS) research on decision support systems (DSS) has a high potential to make solution-oriented and effective contributions to affected market players. DSS contribute to improved decision making through the use of approaches, models and tools that enable the collection of decision-relevant information from data of different types, sizes and sources. Consequently, as the diversity of information and the amount of data available in the rapidly digitalizing energy sector grows significantly, the role of appropriate and customized DSS is becoming increasingly important.

In order to support affected market players in finding the best possible solutions to current and future issues in the field of renewable energies, this thesis presents

and discusses quantitative decision support for various stakeholders on the basis of several research articles with a special focus on the wind market. The thesis is divided into six sections, each dealing with a specific issue and the respective stakeholders. Figure 1 illustrates the thematic structure with corresponding conference and journal publications.

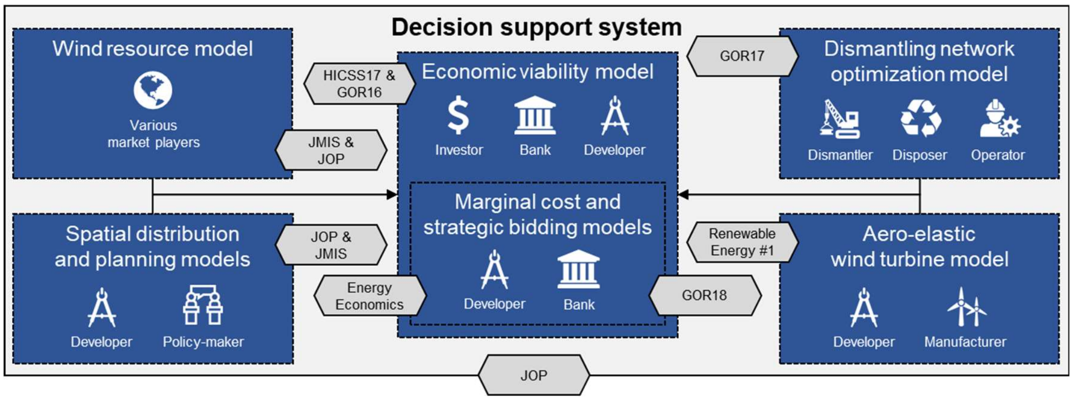

Figure 1. DSS, models, addressed market players and corresponding research articles.

In the following, a short summary of the addressed issues, proposed solutions and related publications is given:

Valuation of Wind Farms under Risk and Uncertainty:

For project developers as well as equity and debt investors the global trend toward market-based support mechanisms means a compression of margins, a greater exposure to risk and less room for errors when investing in wind and solar farms. As a result, current studies forecast substantial additions of renewable energy capacity in the next decades to be at risk due to extensive funding gaps and lower investment activity. The latter is, inter alia, due to difficult and inaccurate risk-return analyses caused by an insufficient understanding of the influence of major risk factors and their correlations. In order to increase the investment appetite in a consolidating market environment, decision support is provided for the identification of investment opportunities that feature specified return requirements and risk-bearing capacity. The corresponding DSS utilizes a probabilistic economic viability model, which combines a discounted cash-flow (DCF) calculation with a Monte Carlo simulation (MCS). Risk factors and their correlations are simulated with the MCS and under consideration of the integration of Iman-Conover (IC) algorithms into the simulation. As shown in Figure 2, the perspective of debt investors is represented through a debt sizing/sculpting module focusing on debt service coverage requirements, while a valuation module represents the perspective of equity investors and enables the analysis of risk-return key performance indicators (KPI).

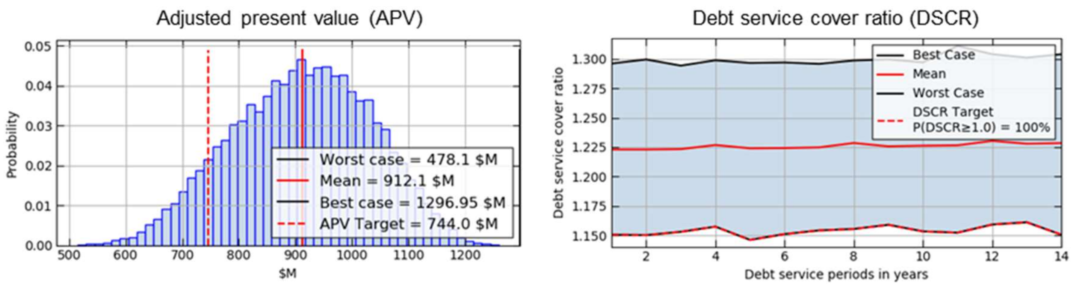

Figure 2. Exemplary risk-return KPIs of the economic viability model.

The applicability of the DSS and the economic viability model is initially evaluated in a case-study of the Mexican wind energy market using data on five currently operating wind farms. In addition, the economic viability model is further evaluated in all subsequent sections, since all presented solutions to the issues considered in this thesis extended this approach with various aspects.

Competitive Bidding in Renewable Energy Auctions

In the context of the shift toward market-based support mechanisms, a large number of countries have opted for the introduction of auctions for renewable energy projects in recent years. Auctions introduce competition among project developers for permissions, financial support, procurement rights and/or remuneration contracts through competitive bidding processes. In current state-of-the-art auctions project developers compete by specifying their demanded sales price (e.g., in ct/kWh) as well as a capacity (e.g., in MW) to be installed and only the most cost-competitive projects with the lowest offered sales prices are granted until the auction volume (e.g., in MW) is reached. Consequently, the new challenge in developing renewable energy projects under auction-based support mechanisms is the precise quantification of competitive and sustainable bidding strategies. In order to enable project developers to be in a competitive position in upcoming auctions, decision support is provided for the optimization of bidding strategies under consideration of the investment requirements of both equity and debt investors and given assumptions about future auction results. For this purpose, the economic viability model from Section 2 is extended by a marginal cost model, which is implemented a strategic bidding optimization (see Figure 3).

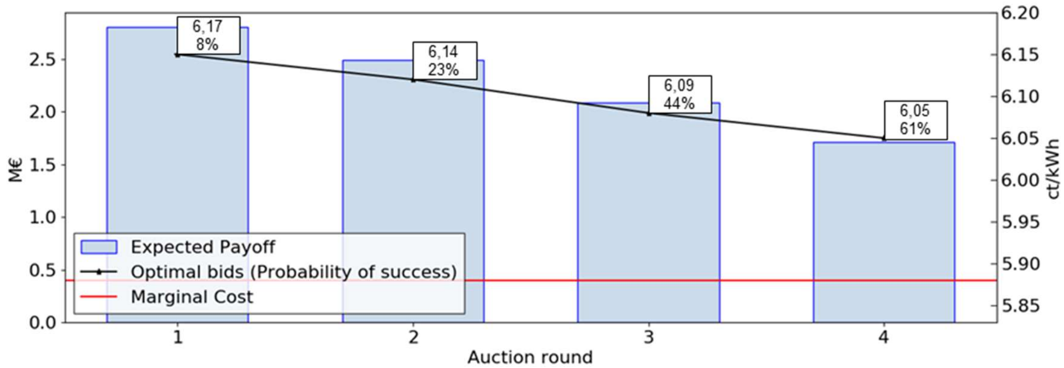

Figure 3. Optimal bidding strategy and expected payoff.

The applicability of the extension is evaluated in a case-study of a project developer participating in the newly introduced auctions for onshore wind farms in Germany. In addition, the marginal cost model is further evaluated in Section 4 and 5, since it is also the basis for the corresponding case-studies.

Politico-Economic Simulation of Renewable Energy Auctions to Design Incentives for a Spatially-Diversified Deployment:

From the perspective of policy-makers, renewable energy auctions enable managing a cost-efficient expansion of deployment through competitive bidding processes and predefined auction volumes determining future capacity additions. The competitive pricing prevents overcompensation of project developers and investors and is likely to result in comparatively low remuneration levels and substantial reductions of financial support over time, as only the most cost-efficient projects are granted. However, as the cost-efficiency of renewable energy projects is highly dependent on the in-situ resources (e.g., wind or solar), an unintentional effect of auctions is the imminent accumulation of renewable energy capacity at most resource-rich locations within an auction area. Due to highly correlated resource availabilities at these locations, the spatial concentration of capacity increases the volatility of electricity supply, which impairs the system integration of intermittent renewable energies and the corresponding costs. In order to enable policy-makers to manage the arising trade-off between cost-efficient renewable electricity supply and reliable and cost-efficient electricity distribution, decision support is provided for the optimal design of auction features incentivizing an appropriate spatially-diversified deployment. For this purpose, the economic viability model from Section 2 and the marginal cost model from Section 3 are extended by a wind resource simulation and an economic agent simulating the investment decisions of equity and debt investors. By applying the approach to a variety of potential wind energy sites in an auction region, appropriate location-based incentives (see Figure 4) can be derived that foster better system integration through diversified spatial deployment of capacity.

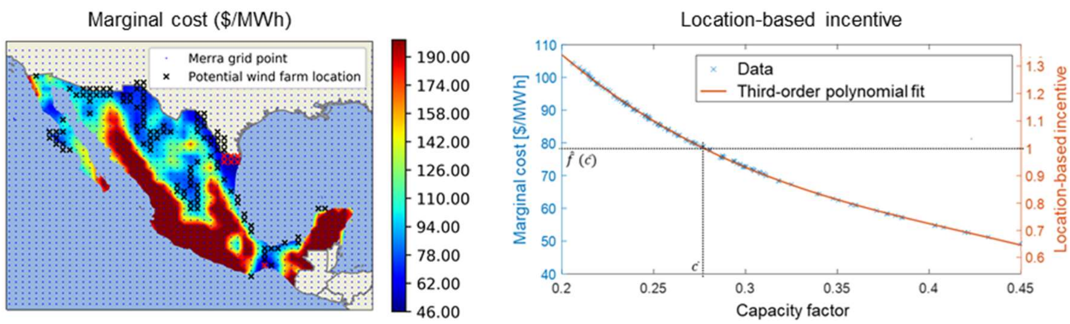

Figure 4. Marginal cost of and location-based incentive for Mexican wind farms.

The applicability of the politico-economic approach is evaluated in a case-study of the recently introduced auction-based support mechanism in Mexico.

Interdisciplinary Techno-Economic Optimization of the Structural Design of Offshore Wind Turbines:

The primary objective in the field of wind energy research is generally to reduce the corresponding technology costs from the perspective of the wind turbine manufacture. This also applies to the area of research on optimal designs for offshore wind turbine substructures. The corresponding engineering models typically minimize the mass of structural designs as a cost indicator. However, a reduction in mass also results in a reduction in reliability and reduces the expected lifetime, which negatively effects the risk-return-ratio due to lost revenues at the end of the life cycle. In order to enable wind turbine manufactures to develop cost-efficient structural designs for offshore wind turbines, decision support is provided that is based on an analysis of the trade-off between variable lifetime and component costs of a substructure design. For this purpose, the economic viability model from Section 2 and the marginal cost model from Section 3 are coupled with an aero-elastic wind turbine model in an interdisciplinary probabilistic modelling approach combining both economic and engineering aspects. The applicability of the techno-economic approach is evaluated in a case-study of an offshore wind farm located in the German North Sea by comparing several more or less durable substructure designs (see Figure 5).

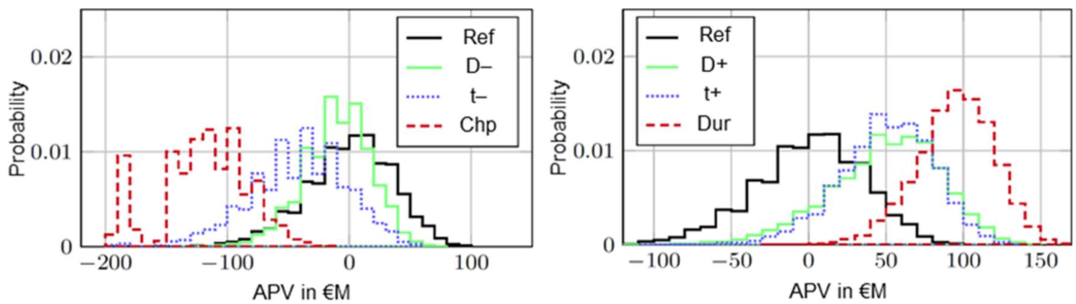

Figure 5. APV of offshore wind farm given different substructure designs.

Results show that a change in paradigm for optimal designs is needed, since the more durable substructure designs feature more appropriate risk-return ratios than the less cost-intensive designs over the entire operational lifetime.

Interdisciplinary Optimization for the Design of Cost-Efficient Dismantling and Disposal Networks for Wind Turbines:

The issue of the operational lifetime is currently also becoming increasingly important in another context, which is the dismantling and disposal of end-of-life wind turbines. In the upcoming years, more and more wind turbines will reach the end of their technical and/or economic lifetime. Consequently, in comparison to past dismantling volumes, the numbers of wind turbines to be decommissioned will increase massively in many countries worldwide. The current state-of-the-art of dismantling wind turbines is to conduct the whole process entirely on-site. However, this is highly time-consuming and implies risks and challenges of ecological, economic, and logistical kind. An option to supersede this undistributed dismantling is to establish a network allowing for a partial dismantling of specific wind turbine components on-site and a later transportation of the partly dismantled components to specialized dismantling sites for further handling. Although the dismantling is more ecological and cost-efficient in the specialized factories, additional costs arise for their initialization as well as additional transports in the network. In order to enable dismantling companies to design efficient dismantling and disposal networks for large numbers of end-of-life wind turbines, decision support is provided that is based on an optimization of the trade-off between dismantling and transportation costs. For this purpose, an optimization model is presented that solves the corresponding location and allocation problems by selecting best locations for the dismantling factories and allocating the dismantling tasks cost-optimally to the possible dismantling sites. The applicability of the optimization model is evaluated in a case-study of a selected region in Northern Germany in which more than 60 wind turbines are to be decommissioned annually over the next five years. Results show that a distributed dismantling and disposal in an optimally designed network has significant cost reduction potentials for the entire end-of-life processing of wind turbines (see Figure 6).

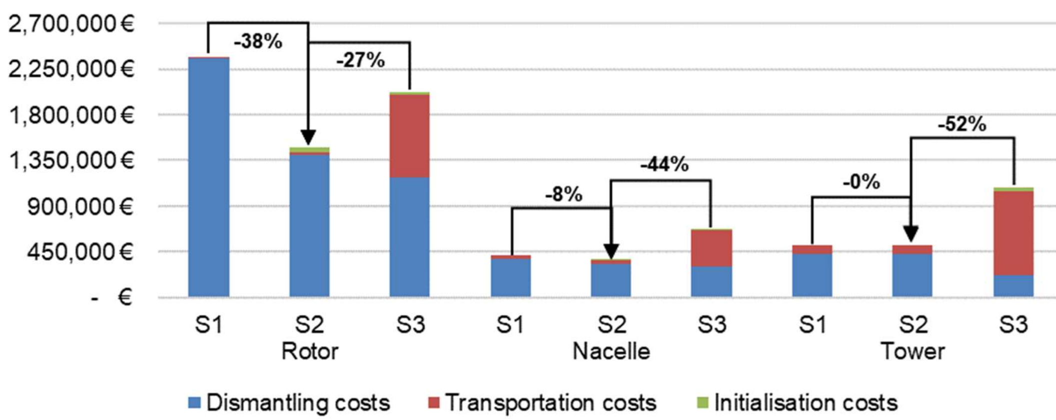

Figure 6. Cost reduction potential of a distributed wind turbine dismantling (Scenario - S2).

Geographic Information System (GIS) Based Analyses to Design Optimal End-of-Funding Strategies for Ageing Wind Turbines:

As mentioned above, the end-of-life of many wind turbines is approaching worldwide. Particularly in Germany a large number of wind turbines will reach the end of their feed-in tariff funding period in the upcoming years. Around 13,000 wind turbines (≈ 16.4 GW) will be affected until the end of 2025. Consequently, operators are increasingly concerned with selecting and designing optimal end-of-funding strategies for their individual turbines (i.e., lifetime extension, repowering or permanent shutdown). Since the operators can only implement these strategies with the help of a wide range of higher-level stakeholders (e.g., project developers, investors, policy makers, wind turbine manufacturers, dismantlers or waste management companies), various other market players at the macro-level are also concerned with end-of-life/funding. In order to design optimal strategies, both spatial and economic aspects must be considered and all possible strategies must be simultaneously examined and permanently compared. However, the current research tends to consider all aspects and strategies separately. In order to enable operators and other higher-level stakeholders to find optimal solutions for end-of-funding strategies, decision support is provided by means of a GIS that simulates and compares all possible end-of-funding strategies for an individual wind turbine or wind farm and selects the best strategy by solving an optimal stopping problem based on the risk-return-requirements of the corresponding operator. For this purpose, the economic viability model from Section 2 and the wind resource simulation from Section 4 are supplemented by a differential investment analysis and coupled with a spatial planning model.

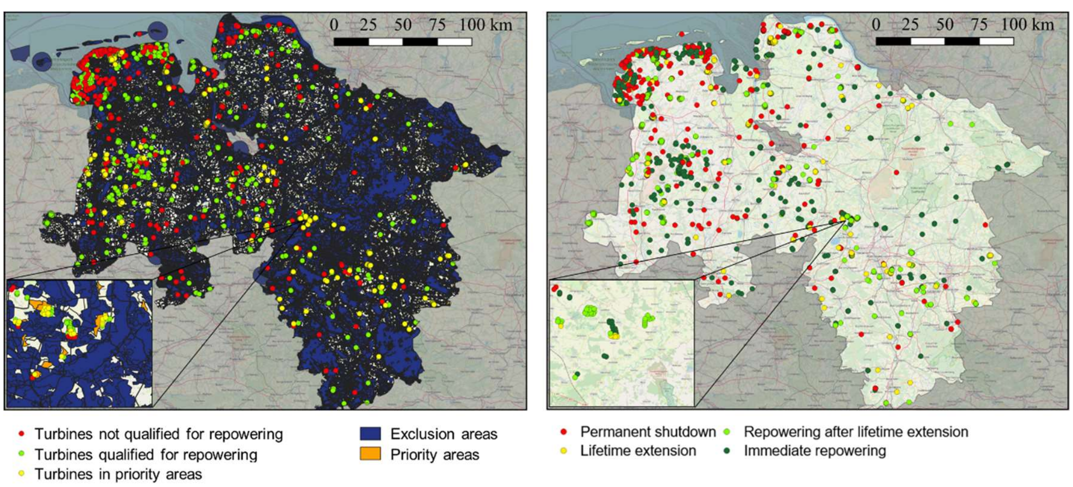

Figure 7. Optimal end-of-funding strategies for the wind fleet of Lower-Saxony.

The underlying modelling approach enables analyses in different spatial scaling, reaching from detailed analyses on single turbine or wind farm level up to macro-level analyses of entire wind fleets. The applicability of the GIS-based approach is evaluated in a case-study of the 1,645 wind turbines located in Lower-Saxony reaching the end of their feed-in-tariff funding by 2021 (see Figure 7). Results show high repowering and lifetime extension potentials in the German wind fleet, which must be exploited to the full extent due to the decreasing availability of new green field areas in Germany, in order to enable the wind industry to continue playing a pioneering role in the energy transition.

In this thesis, current challenges of the changing renewable energy market are investigated and tackled with IS research. The resulting findings of the corresponding publications mainly address two objectives. On the one hand, they point out the strength and necessity of IS research in terms of its integrating function between other research areas (here: renewable energy finance and policy, wind resource assessment, spatial planning, structural dynamics, and logistics). On the other hand, they respond to the need for more practical assistance for decision makers in this context, as outlined by Dedrick (2010), by providing DSS specifically addressing practical problems of various renewable energy market players (here: project developers, investors, policy-makers, wind turbine manufacturers, dismantlers, disposers, and operators).

For the purpose of designing the DSS in light of the two main principles of IS research – rigor and relevance – well-established design science research (DSR) approaches oriented toward Peffers et al. (2008) and Hevner et al. (2004, 2007) were employed for the research presented in this thesis. This involved the identification of domain-specific problems, the specification of well-defined research objectives and corresponding questions as well as the design, development, demonstration, evaluation and communication of technological artifacts in a loop of process iterations, as proposed by Hevner (2004). The conducted research additionally addresses the relevance principle by focusing on the contribution of DSS solutions to real-world issues and challenges. Following the DSR knowledge framework of Gregor and Hevner (2013) the resulting technological artifacts can be classified as nascent design theories, since they establish certain generalized design principles, which can be useful for the development of other artifacts that address related issues and challenges.

In summary, this thesis shows that quantitative decision support based on rapidly growing volumes of data directly contributes to the needs of market players in an increasingly digitalized (renewable) energy market by improving the decision-making process through aggregated information. Consequently, as information is a prerequisite for making appropriate decisions on sustainability actions (Malhotra et al., 2013; Gholami et al., 2016; Seidel et al., 2017), IS research on DSS has a tremendous potential to make solution-oriented and impactful contributions to the mitigation of global warming and issues surrounding the transition toward renewable energies.

III. Index of Content

Preliminary Remark: Overall View of Publications

Table 1. Overview of publications.

#	Publication Date	Title	Authors	Conference/Journal	VHB/JQ3	WKWI	Section	Appendix
9	07/2020	Competitive and Risk-Adequate Auction Bids for Onshore Wind Projects in Germany	Stetter, C. Piel, J.-H. Hamann, J.F. Breitner, M.H.	Energy Economics, In Press, Journal Pre-proof	B	-	3	9
8	08/2019	Enhancing Strategic Bidding Optimization for Renewable Energy Auctions: A Risk-Adequate Marginal Cost Model	Stetter, C. Piel, J.-H. Koukal, A. Breitner, M.H.	Operations Research Proceedings 2018, Dresden, Germany, pp. 217-223.	D	-	3	8
7	06/2019	Influence of Structural Design Variations on Economic Viability of Offshore Wind Turbines: An Interdisciplinary Analysis	Hübler, C. Piel, J.-H. Stetter, C. Gebhardt, C.G. Breitner, M.H. Rolfes, R.	Renewable Energy, 145, pp. 1348-1360.	-	-	5	7
6	04/2019	Lifetime Extension, Repowering or Decommissioning? Decision Support for Operators of Ageing Wind Turbines	Piel, J.-H. Stetter, C. Heumann, M. Westbomke, M. Breitner, M.H.	Journal of Physics: Conference Series (JOP), 1222 (2019), 012033.	-	-	7	6
5	05/2018	An Optimization Model to Develop Efficient Dismantling Networks for Wind Turbines	Westbomke, M. Piel, J.-H. Breitner, M.H. Nyhuis, P. Stonis, M.	Operations Research Proceedings 2017, Berlin, Germany, pp. 239-244.	D	-	6	5
4	05/2018	Decoupled Net Present Value – An Alternative to the Long-Term Asset Value in the Evaluation of Ship Investments?	Schrader, P. Piel, J.-H. Breitner, M.H.	Operations Research Proceedings 2017, Berlin, Germany, pp. 271-276.	D	-	-	4
3	12/2017	Promoting the System Integration of Renewable Energies: Toward a Decision Support System for Incentivizing Spatially-Diversified Deployment	Piel, J.-H. Hamann, J.F. Koukal, A. Breitner, M.H.	Journal of Management Information Systems (JMIS), 34(4), pp. 994-1022.	A	A	4	3
2	07/2017	Applying a Novel Investment Evaluation Method with Focus on Risk – A Wind Energy Case Study	Piel, J.-H. Humpert, F.J. Breitner, M.H.	Operations Research Proceedings 2016, Hamburg, Germany, pp. 193-199.	D	-	-	2
1	01/2017	Financial Decision Support System for Wind Energy – Analysis of Mexican Projects and a Support Scheme Concept	Koukal, A. Piel, J.-H.	Proceedings of the 50th Hawai'i International Conference on System Sciences (HICSS), Big Island, Hawaii, USA, pp. 972-981.	C	B	2	1