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Contributions to the institutional economics of the energy transition

Klaus Eisenack
Julien Minnemann
Paul Neetzow
Felix Reutter

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Department of Economics
University of Oldenburg, D-26111 Oldenburg

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Editor: Klaus Eisenack

Contributors:

Klaus Eisenack

Julien Minnemann

Paul Neetzow

Felix Reutter

Abstract

What can institutional economics offer to analyze and shape the transformation of electricity systems towards a low-carbon future? This volume presents papers from a postgraduate research course in “Sustainability Economics and Management” in the winter term 2014/15. The introductory chapter sketches potential contributions from institutional economics and provides an overview of the course’s topic and the other chapters. The second chapter presents an institutional comparison of different options to integrate electricity storage into the system. The third chapter analyses the effect of different market structures for investment in electricity storage. The final chapter proposes and investigates a novel auctioning mechanism for offshore grid expansion.

Contents

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Institutions and the Energy Transition: Some Overview

Klaus Eisenack*

Electricity systems rapidly change all over the world. It is yet unclear how this process can be organized in an appropriate way. This chapter introduces into the volume, produced by a postgraduate project course on the institutional economics of the energy transition.

Change of electricity systems is driven, i.a., by technological progress, economic and demographic development, and energy security concerns in the light of unaccessible or exhausted fossil resources (see, e.g., IEA, 2014). Concerns about the risks of nuclear energy and environmental stress from conventional energy production motivate policies to fundamentally transform energy systems. In particular, climate change is forced by anthropogenic greenhouse gas emissions (IPCC, 2013), of which currently about two thirds are caused by combustion of fossil fuels (IEA, 2015).

One showcase for transforming an energy system is the German “Energiewende”. Starting with the 1990ies, German governments heavily subsidized renewable electricity generation like wind and solar power. In parallel, the European electricity sector became liberalized (with EU Directive 2003/54/EC being a milestone), which included the introduction of electricity markets and (legal) unbundling of electricity grid operation from generation. Since 2005, greenhouse gas emissions from the electricity sector are regulated under the European emissions trading system. After the Fukushima ac-

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*Email-address: klaus.eisenack@uni-oldenburg.de; Carl von Ossietzky University Oldenburg, Germany

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cident (2011), the German government pushed through a previously contested plan to fade out nuclear power in Germany. A set of policy goals were defined, including quantified targets for greenhouse gas emission reductions, share of renewables, and energy efficiency. These goals drove the political debate and many regulatory reforms during the last years, e.g. the design of renewable subsidies, the planning of grid expansion investment, and the future market design.

Electricity can be characterized as an essential factor of production in modern economies, and is even classified as a critical infrastructure (BMI, 2009; Moteff et al., 2003). On the other hand, the economic costs of transforming an electricity system are substantial. It is consequently of utmost importance to understand how an energy transition can be organized in a legitimate, equitable and efficient way in order to achieve precise goals. This is a technological challenge, but also a question about how to design policy instruments and markets, laws and regulations, contracts and responsibilities — namely, a question of the appropriate institutions.

In this volume, institutions are broadly understood as the formal or informal rules that shape human interactions (North, 1990). Since decades, new and contemporary classic institutional economics has researched issues like the governance and design of contracts, collective choice arrangements and the management of common property resources, economic development and institutional change. The analytical starting point is an imperfect world characterized by interdependent actors, uncertainty and positive transaction costs. Hence, it seems quite natural to ask for the contributions from institutional economics to organize and analyze an energy transition. A first indicative literature search undertaken in our project has yet revealed that this nexus has not been so extensively studied up to date.

This introduction is intended to lay out the background of the subsequent chapters in the volume. Its next section sketches some potential entry points of institutional economics for studying the energy transition. The subsequent section informs about the postgraduate course and summarizes the students' papers. The chapter closes with short conclusions.

Some institutional issues of the energy transition

There are many aspects of organizing an electricity system and its transition that might be highlighted. I start with a short set of selected references that employ institutional economics concepts to analyze electricity systems (or come close to doing so). Note that the focus is not on energy in general, but on electricity in particular. This section then discusses some issues in more detail. I neither claim to present an exhaustive list, nor a ranking of issues.

Sovacool (2014) stresses the general paucity of social science research on energy issues. Suggested institutional research avenues in his review paper include the political economy of energy systems, and the interlinkage of international, subnational, private and public actors. Some theoretical contributions on infrastructure industries put the complex technological interdependence of the various components of an electricity system into the center (Finger et al., 2005; Kuenneke et al., 2010). Hauteclocque and Perez (2011) discuss reform of electricity sector regulation from a property rights perspective. There are some comparative studies of institutional diversity of grid regulation and market design, taking account of interconnectedness in the short run, long run, and cross-border trade level (Erdogdu, 2013; Rious et al., 2008). Some others view energy systems through the polycentricity lens (Goldthau, 2014; Sovacool, 2013), a concept dating back to Ostrom et al. (1961), or through the public choice lens (Gawel et al., 2014).

Electricity grid regulation, vertical integration, public procurement and franchise bidding have been analyzed for quite a while (e.g. Crocker and Masten, 1996; Demsetz, 1968; Gilbert and Newbery, 1994; Goldberg, 1976; Joskow, 1985; Lewis and Sappington, 1991; Libecap and Wiggins, 1985; Trebing, 1987). Issues in this field are the role of credibility and uncertainty in regulation. Examples for more recent publications with an institutional angle are Bickenbach et al. (1999); Fabrizio (2013); Fremeth and Holburn (2012); Jarvis and Sovacool (2011); Perez (2005). Grid regulation becomes a specific twist if grid expansion is additionally considered. Beckers et al. (2014) provides a general overview of multiple aspects with taking the German energy transition as a case study.

Investigating grid expansion touches issues of different grid ownership models (equity/debt, public/private), stretching to models of shared ownership by local citizens. These topics are also studied for ownership of generation capacity and energy cooperatives (Müller and Rommel, 2011; Viardot, 2013; Walker and Devine-Wright, 2008; Wolman, 2007; Yadoo and Cruickshank, 2010). There are also analyses of alternative business models and the associated contractual hazards (e.g. energy savings insurance, supply of new electricity storage technologies; Anuta et al., 2014; Greene, 2011; Mills, 2003).

Entry points for analysis

Some particular features of the electricity sector are, I would like to argue, of particular importance for the institutional analysis of the energy transition. Although some of them play a crucial role regardless of a theoretical position, they are somehow natural entry points for an institutional economics perspective:

(F1) Electricity transport and electricity trade require a complex and expensive infrastructure with economies of scale.

(F2) Both electricity generation and transport frequently require lumpy (i.e. large and undivisible) investments with long life times.

(F3) Electricity generation and demand is subject to short-term fluctuations which are not easy to predict.

(F4) Electricity transport needs to be operated such that the laws of electrodynamics are followed. Kirchhoff's laws require (i) to balance all fluctuating producers and consumers at each instant in time, and (ii) to take care of loop-flows in a meshed grid.

(F5) Electricity can, by and large, only be stored at high cost or with substantial losses.

(F6) Electricity is an essential factor of production in modern economies.

All this implies that setting up a market for electricity is associated with high fixed costs. These costs are composed of ordinary transaction costs of establishing and running the market, and the costs of establishing and running the technical infrastructure. Electricity markets are expensive public goods. I now derive some selected issues for research from these entry points.

Collective choice on the short time scale (from F1, F3, F4, F5)

In the short run, there is considerable interdependence between different components of an electricity system. An electricity system can be conceived as a single entity that stretches from every power plant, via electricity lines and transformers, to the plugs and spinning engines of each consumer. Its operation requires coordination between many actors: producers, consumers, operators of transport and of distribution grids.

Collective choice is required for many reasons. Grid stability requires balancing of load and generation at each point in time, and also considering loop-flows. In the more extreme case of disruptions or possible blackouts, decision have to be made about which parts of the grid are shut down first to keep others stable. Electricity system stability can be considered as a public good of all actors that own facilities in the system or are connected to the system.

To make things more difficult, all such collective decisions need to be made in run-time. Although there might be good operation plans for each next day, they inevitably require adjustment in each second. Run-time collective decisions cannot be made solely with markets – designing markets that can adjust on such short time scales within the physical constraints of the grid likely leads to an extremely inefficient level of transaction costs.

On the short time scale, other institutional arrangements than markets are needed, or markets need to be complemented with further arrangements like hierarchies, routines or responsibilities that support fast and reliable operational choice. Some institutionalized routines might even be incorporated in technological devices. If run-time operation is supported by contracts and markets, these contracts require the ability to deal with uncertainty, i.e. they are incomplete. As canceling or renegotiating a contract in run-time is practically impossible, there is always some leeway for opportunism for the contracting parties. Such contracts do also need to stipulate how to deal with electricity not delivered. Non-delivery does not only damage the other contracting party, but probably all users of the electricity grid if it puts grid stability on risk (external effects). Markets for balancing energy are real-world examples of how to deal with these issues. These markets are usually complemented with hierarchical components.

There are also issues of ownership and control. With the liberalization of electricity markets, the grid (being the monopolistic bottleneck) is frequently unbundled from electricity generation. If grid operators are not allowed to produce electricity on their own, they are forced to obtain balancing energy via contractual solutions. It is an open question whether balancing might be possible at lower transaction costs for a vertically integrated utility or an integrated system operator.

Collective choice and contracting on the long time scale (from F1, F2, F4)

In the long run, there is considerable interdependence between different components of an electricity system. All components need to be constructed so as to fit to each other, but they can usually not be built all at the same time. When they are built they become constraints for other components due to their long life times. This requires to solve long-term coordination problems: procedures and property rights structures that take care of potential path dependencies and reduce the likelihood of inefficient investment paths.

One practical question is, for example, whether expansion of new (renewable) power plants shall follow the grid topology, or whether the grid topology shall follow the plans for expanding renewables or fading out conventional power. In an ideal world, one would plan both together. But that is not easy in practice due to irreversible large-scale investment. Different actors control different parts of the electricity system, but both grid and generation investments are highly asset specific (bilaterally).

Costs can be externalized between power plant and grid operators. If there are multiple grid operators, it is possible that “profitable expansion can be bad” (Brunekreeft, 2004): It might be profitable for one operator to expand one power line. Yet, due to loop-flows, this might reduce the line capacity of another operator, and thus total system costs increase.

These issues require careful planning procedures that cannot be resolved by simple contracts. At least trilateral governance seems to be appropriate, or more elaborate legal institutions.

Market power, ownership and control (from F1, F2, F6)

The above arguments might support more vertical integration in the electricity sector, in particular if the collective choice issues become more pressing with a large share of fluctuating renewables. On the other hand, electricity grids and sometimes power plants tend to be natural monopolies. This requires specific contracts or market regulation to avoid misuse of market power.

In liberalized electricity markets, the price for grid access is frequently regulated by a public agency. Another model is public procurement. Market regulation is an old topic in regulatory economics, industrial organization and institutional economics. In addition to economies of scale, the electricity sector is prone to a set of well-known problems like asymmetric information and specific knowledge in operating distribution or transportation grids. There is a considerable degree of asset specificity in many electricity sector investments. One bottom line for the private supply of essential services is undiscriminated access. This is particular important for the integration of renewable capacities from new market entrants into the grid, so that incumbents do not hinder the energy transition.

Another issue is the regulation of expansion investment. Many established institutions aim at striking a balance between cost efficiency and cost recovery for a power grid of more or less fixed size. But some argue that larger or smarter grids are needed to integrate fluctuating renewables. What are the appropriate grid investment costs that shall be accountable in regulatory formulae? Who shall decide about appropriateness in this context? The well-known problems of electricity sector regulation are attenuated by the long-term uncertainties about technological progress (e.g. in storage technologies and demand-side management), that partially determine the future need for additional grid capacities.

Further, these issues can be addressed by rearranging ownership and control. If distribution grids would be owned and controlled by municipalities or local citizens ("grid cooperatives"), the balance between the objective of cost-efficiency and disciplining market power might be achieved at lower transaction costs. For transportation grids, this approach is more difficult to evaluate, as externalities spill over long distances. New models of grid ownership would need to find the appropriate institutional level.

Institutional change (from F1, F2, F6)

An energy transition is a process of both changes in technologies and institutions. Institutions are crafted in order to incentivize changes in the technologies employed, and institutions change as a reaction to new technologies.

A common approach to study institutional change is the 'discriminating alignment hypothesis' that institutional arrangements are selected so as to decrease the sum of production and transaction costs (Demsetz, 1967; Williamson, 2000). This contrasts the position that institutional change is mainly driven by particular interests (cf. Krueger, 1974; Paavola, 2010; Tollison, 1982). Since electricity is an essential factor of production, it is quite reasonable that institutions, institutional design and institutional change tend to be highly politicized. Thus, the latter approach might be particularly interesting when researching how electricity systems change.

There are, however, some limitations to both approaches, as institutional and technological change are so strongly interwoven in a large-scale energy transition. Approaches of institutional fit (Young, 2002) typically take the properties of the (technological) resource as given and analyze how different institutions deal with the resource. Many other studies, in contrast, start analytically from the institutions (like feed-in tariffs, carbon prices or subsidies schemes) and determine how they influence investment decisions and technology choice. In practice, however, the long life times of both institutions and technologies in the electricity sector make them co-evolve. The co-evolution of resources and institutions is yet not so frequently studied in institutional economics (see Libecap, 2007, for an example), but understanding this co-evolution might benefit from improvements in theory.

Practical project in Sustainability Economics and Management

Based on the issues laid down in the previous section, this volume presents papers from three postgraduate students in the master course "Sustainability Economics and Management" at Carl von Ossietzky University Oldenburg, Germany[1]. Each student in this course of study has to participate in a one semester "practical project", but can select between different alternative projects. Their general teaching objective is to enable students to put their theoretical education into practice. They shall go deeper into a specific topic, develop responsibility for self-governed action, and train soft skills like team work. The project where this volume was prepared took place in the winter term 2014/15. It was somehow unconventional in that it did not focus on interaction with partners from practice outside academia (as common in such projects), but on "academic practice". It was designed for students (i) who were particularly interested in the announced topic ("The Institutional Economics of the Energy Transition"), either in institutional economics, or in the German energy transition, or both, and (ii) who were interested in learning about and exploring their own capabilities to undertake scientific research. Participation required familiarity with both institutional and energy economics. The latter is a compulsory lecture in "Sustainability Economics and Management", and the former is offered as an elective. In light of these high expectations, five students joined the project. Its stated objective was to individually produce manuscripts that are in principle suitable for submission to a peer-reviewed journal.

The project's work primarily consisted of joint reading and development/writing of own scientific papers. My own role as teacher is more appropriately described as a supervisor, discussant, co-learner and convenor. While the final papers were written individually, teamwork and collaborative learning played a crucial role. We conceived the project as a joint scientific workshop. We discussed our understanding of jointly read papers in our weekly meetings, collaboratively planned and shared the insights from individual literature search, and gave extensive feedback to our ideas and emerging

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[1] http://sem.uni-oldenburg.de/

manuscripts. There were no grades awarded for within-semester performance. Grades were only given for the final papers in order to sustain the workshop atmosphere and maximize the flow of honest substantive critique. Yet, many additional contributions were compulsory for every project participant.

The first part of the semester started with joint reading of essential and seminal papers that were selected by myself. In parallel, students developed one-pagers about their intended research (including statement of research question, first literature, planned methods and time plan) during the first two weeks. These where then jointly (and critically) discussed in the group. Students were given the opportunity to adjust or change their research plans. The second part of the semester was mostly used for literature work. While students worked on their research plan, we agreed on a set of papers (retrieved from parallel literature search of the students) for joint reading or for being reported to the whole group. Two sessions in the second part were devoted to lectures from myself: one on paper development, the other on paper writing, the peer review process and about how to write a paper review. The third part (at the end of the semester) started with a mini-conference where every participant presented her/his work in progress in a conference style. Other (more experienced) postgraduate students where invited to this mini-conference. Afterwards, we entered a simulated peer-review. Students had to submit their papers. For each paper, two quasi-anonymous reviewers were selected from the project participants. I served as "editor". Some students chose to drop out after "major revisions", but all contributed with reviews.

The following three chapters of this volume are the three out of five papers that were finally "accepted for publication".

Reutter (2015) investigates the integration of novel battery storage technologies into the electricity system. Recent development of storage technologies makes it likely that they can be run economically in some years. This would substantially ease the balancing of fluctuating renewables. The question is about who shall own and operate such storage power plants in which parts of the system. The paper compares four options: storage run by renewable power plant operators, by transport system operators (TSOs), by independent firms, or by electricity consumers. In the context of the present regulation, subsidies schemes and market designs in Germany, most of the considered options are not particularly attractive for investors. From a system perspective an efficient deployment of batteries by renewables producers might occur if some flexibility components will be integrated in the subsidy schemes, and if the balancing market will be redesigned. Efficient employment by TSOs requires adjustment of incentive regulation, and by independent firms an adjustment of the intraday market design.

Neetzow (2015) also analyzes electricity storage. He develops an analytical storage capacity investment model that considers optimal short-run operation on the second decision stage. The model is solved for a competitive and a monopolistic market. General difficulties stem from the two different physical capacity parameters: maximum (positive or negative) load, and maximum storable energy. The monopolist choses both types of capacity at inefficiently low levels. Storage becomes more profitable with increasing variability of load (due to peak shaving), and for a higher average residual load. Thus, the question whether a rising share of fluctuating renewables leads to more investment in storage capacity (as frequently requested by proponents of the energy transition) is an empirical one.

Minnemann (2015) shifts the focus from electricity storage to offshore grids. Due to large-scale investment in offshore wind power generation in Germany, new and expensive electricity transport infrastructure needs to be constructed. By regulation, TSOs have the responsibility to connect offshore power plants to the grid. There have yet been substantial delays in the past. There are cases of readily built wind parks that are not able to feed in. The paper thus argues that current grid regulation is not sufficient to resolve the problems of offshore grid expansion. Instead, it proposes and analyzes an improved version of a Demsetz auction. In contrast to the standard case, the right to operate an offshore connection is auctioned together with the obligation to construct the connection. Bids can be made by consortia without (incumbent) TSOs. The new power lines are then exempt from the standard onshore incentive regulation, but grid fees can only be collected from connected wind parks. This arrangement reduces incentives for opportunism compared to the current situation.

Conclusions

This introduction has presented the background of a postgraduate project in "Sustainability Economics and Management". It reflected on the energy transition and likely contributions from institutional economics to address this issue of high societal relevance with academic means. The previous section has introduced the teaching concept behind the project, and gave a summary of the papers in this volume.

I hope that you will enjoy reading the following papers, as I did myself. Thanks go to all participants of the project (I. Eichelberg, J. Minnemann, P. Neetzow, F. Reutter, W. Staiger), in particular for contributing to the discussions, the peer review and publication process. It would be great if this volume would motivate future students to dive into scientific work, and if it is perceived as a small but valuable contribution to the institutional economics of the energy transition.

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Battery storage business models and their positive real-time balancing externalities

Felix Reutter[*]

Abstract

To maintain the stability of an electricity system its electric feed-in and output must be continuously balanced. Therefore, the expansion of intermittent renewable energies increases the flexibility requirements of electricity systems. This paper outlines and analyzes different conceivable business models for battery storage. It is argued that all considered battery storage options can bring benefits for the electricity system in terms of its real-time balancing needs. Considering the regulation of the electricity sector, the designs of the electricity markets, and the support policies for renewable energies and battery storage systems, key institutions influencing the diffusion of the battery storage options in Germany are identified. I find that the present German institutional framework does not financially reward all considered battery operators for supporting the real-time balancing of the electricity system. Namely, transmission system operators (TSOs) using batteries as network assets and operators of renewable energy facilities using batteries for trading on the balancing markets cannot adequately financially benefit from the system support that they induce. I suggest how these positive external effects could be internalized by adjustments to the present institutional framework such that the overall economic efficiency of the electricity system can be enhanced.

Keywords: electricity, intermittent RES, system stability, economic efficiency, institutional analysis, Germany

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[*] Email-address: felix.reutter@web.de; Carl von Ossietzky University Oldenburg, Germany

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1 Introduction

After the Fukushima nuclear catastrophe in 2011 the German government announced its decision to accelerate the transformation of the energy system ("Energiewende"), comprising a complete phase out of nuclear power by 2022 and a conversion of the system to renewable energy sources (RES). In 2014, RES accounted for 27 percent of gross electricity consumption in Germany (Statistisches Bundesamt, 2015). According to the German Renewable Energy Act (EEG), it is planned to expand this share up to at least 80 percent in 2050. Wind power and photovoltaics (PV) play the most important role for this plan.

In contrast to fossil energy sources, these RES are intermittent. Therefore, the flexibility requirements of the electricity system will increase as it is necessary for a stable operation of the system that the electric feed-in and output are continuously balanced (Agora, 2014). Among several other flexibility options, battery storage could help to cope with the emerging flexibility requirements (Benger et al., 2013).

There is already a comprehensive strand of literature dealing with the technical characteristics of different battery storage types (e.g. Dunn et al., 2011; Poullikkas, 2013; Alotto et al., 2014). In this paper the term battery is used to describe all technical forms of rechargeable electrochemical batteries. Another strand of literature concerns the life cycle costs of different battery types (e.g. Battke et al., 2013; Zakeri and Syri, 2015). Some publications also consider economic and legal aspects of different battery storage systems (see references in section 3). Furthermore, a number of engineering oriented studies identify possible technical battery storage applications (e.g. Denholm et al., 2013; Rodrigues et al., 2014; Suberu et al., 2014). However, there is so far a gap in the literature analyzing conceivable business models for battery storage with respect to key institutions for their diffusion, and with respect to questions about the impacts their diffusion would have on the whole electricity system in terms of its real-time balancing needs and how these impacts are reflected in the economic variables relevant for the battery storage operators.

I address this gap in the present paper. Starting from four fundamental positions where batteries could be located within the electricity system, I outline business models for battery storage systems. I identify key institutions that influence the chances of success of these business models. Moreover, I analyze whether a diffusion of the business models would be beneficial in terms of the real-time balancing requirements of the electricity system. Finally, I consider whether the battery operators will financially benefit if their batteries support the electricity system with respect to its real-time balancing needs or whether there will be positive external effects in this respect. For the latter cases, I suggest how the externalities could be internalized. In general the paper takes up the insight of institutional economics that the allocation of property rights and other institutional arrangements considerably influence economic outcomes.

The analysis is based on reviewing, analyzing and further developing existing literature on storage systems (cited in chapter 3). It is conducted for the specific institutional settings in Germany since it is the largest country in the European Union. Nonetheless, the approach and some results could also be transferable to other countries aiming for higher shares of intermittent RES.

I find that all considered battery storage options are in principle compatible with the present German regulations being considered as key institutions for the respective business models. Moreover, I argue that all considered battery storage systems can be beneficial for the electricity system with respect to its real-time balancing needs. However, I find that at least two of the considered business models are characterized by positive external effects in this respect. I make suggestions about how these could be internalized.

The remainder of the paper is organized as follows. Section 2 sets out the analytical approach. Section 3 presents the analysis and results. Section 4 summarizes and concludes.

2 Approach

The applied method in this paper for categorizing battery storage systems is based on Anuta et al. (2014) who suggest analyzing energy storage systems with respect to their locations on the grid, their ownership structures, and their target services and revenue streams.

With regard to possible locations on the grid and ownership structures of batteries, I identify and analyze the following four fundamental options for battery storage systems:

(1) “Batteries as network assets” – Batteries are owned and operated by transmission system operators (TSOs) and are located within the grid so that they can support its operation[1]. (2) “Independent batteries” – Batteries are owned by independent battery operators and are randomly located in the network. (3) “Batteries for RES facilities” – Batteries are owned or contracted and operated by (large-scale) RES facilities and are co-located with them. (4) “Home batteries for PV” – Batteries are owned and operated by owners of PV systems and located in the buildings with the PV. These four options for the location and operation of batteries cover most of the battery storage systems discussed in the literature[2].

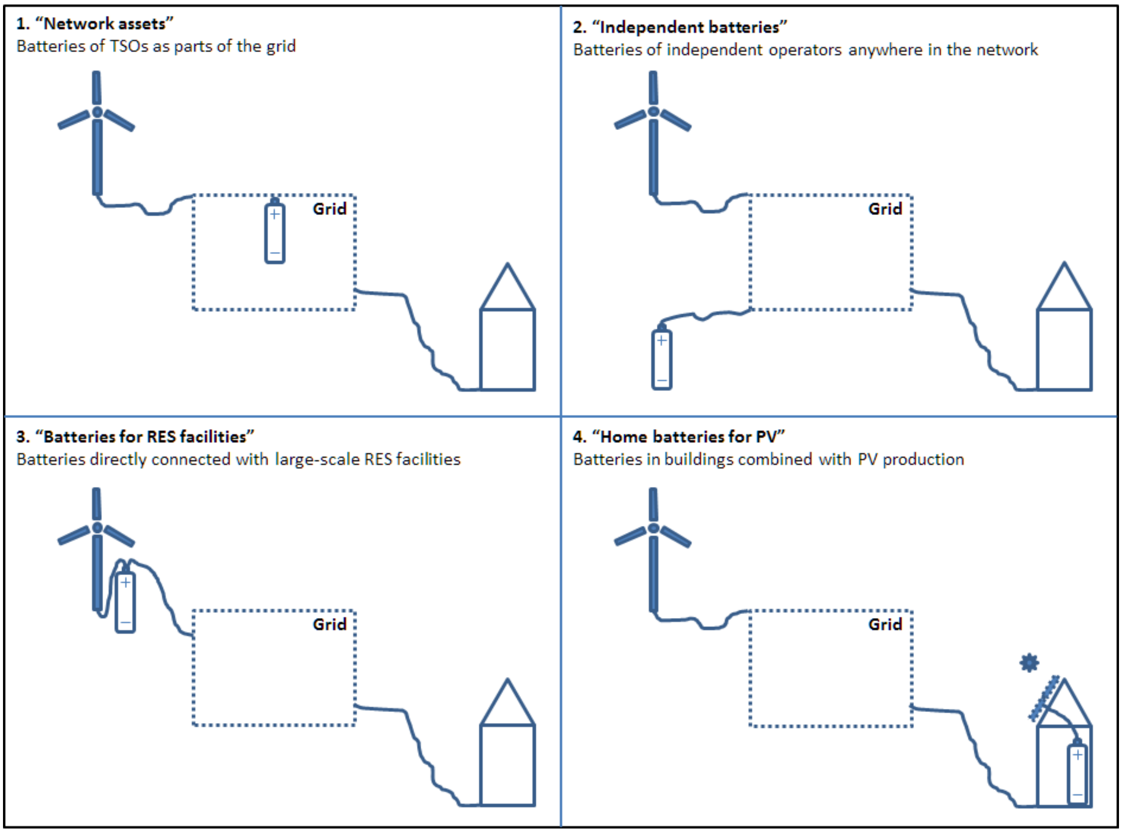

Figure 1: Schematic overview of the four considered battery storage options

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[1] An operation of batteries by distribution system operators (DSOs) within the distribution grid could also be possible (Anuta et al., 2014). Further research should also study this battery storage option.

[2] However, the compilation does not claim to capture all possible battery storage systems. For instance off-grid island applications (e.g. Akikur et al., 2013), battery electric vehicles (BEVs) (e.g. Richardson, 2013), and batteries of final consumers being operated in combination with flexible retail prices (e.g. Ruester et al., 2012; Wang et al., 2013) are not considered in this paper.

With regard to the batteries' target services and revenue streams, I outline business models for the four battery storage options. Generally speaking it holds that, considered in isolation, the use of a battery is economically rational for someone if the additional (discounted) revenues that can be created by the battery are greater than its (discounted) life cycle costs (LCC) – i.e. the costs for the investment, operation, maintenance, and disposal or recycling of the battery. In other words, the net present value (NPV) of the battery investment must be positive.

With reference to institutional economics, a basic idea of this paper is that the NPV and the practical applicability of the different battery storage systems are significantly determined by institutional factors. Therefore, I identify key institutions for each business model as having an influence on their diffusion. Namely, the present regulatory framework for the electricity sector, the design of the relevant electricity markets, and the support policy for RES and battery storage systems are taken into account.

The central proposition of this paper is that the different battery storage systems could come along with positive external effects with respect to the electricity system's needs for real-time balancing interventions. If TSOs have to undertake interventions for real-time balancing, e.g. by activating balancing power, this is associated with costs. The deployment of batteries could help to reduce the needs for such interventions and thereby reduce system costs. On account of this, I discuss for the different battery systems whether their diffusion would reduce the needs for real-time balancing interventions and, if so, whether the related battery operators could financially benefit from that. Where batteries support the system but their operators cannot financially benefit from that, there would be positive external effects. Such externalities typically lead to inefficient results, i.e. to an undersupply of the concerned good (namely the batteries), compared to what would be optimal from a system perspective. Therefore, I make recommendations for these cases on how the externalities could be internalized.

3 Analysis and results

3.1 Batteries as network assets

In the first scenario looked at, batteries could be used as network assets. The TSOs being in Germany responsible for a stable operation of the electricity system could own and operate batteries as elements of the transmission grid in order to assist and improve the transmission services. This is discussed e.g. by Wasowicz et al. (2012), Benger et al. (2013), Heller (2013), and Riewe and Sauer (2014).

The economic rationale of TSOs for investing in batteries could be additional profits that exceed possible additional profits from alternative expenditures. Additional profits from batteries could arise for TSOs if the use of batteries led to cost savings in operating the network that are higher than the batteries’ LCC. For TSOs, such a cost advantage of batteries could, among other sources, especially stem from saved expenses for balancing power (Rodrigues et al., 2014).

Key institutions

The economic decisions of TSOs are extensively determined by the regulation of the electricity sector. Thus, the electricity regulation is a key institution deciding if TSOs have an incentive to invest in batteries. Two questions are particularly important in this context: (1) are TSOs allowed to operate batteries considering the European unbundling requirements? And (2), could TSOs benefit from the operation of batteries?

Concerning the first question, the EU unbundling directive 2009/72/EC which is implemented into the German Energy Act (Energiewirtschaftsgesetz) is of relevance as it prohibits TSOs from generating and selling electricity. However, as Benger et al. (2013) and Riewe and Sauer (2014) argue, the deployment and operation of batteries by TSOs would not infringe these unbundling requirements as long as the batteries are merely used to support the operation of the electricity network without being active on competitive electricity markets.

Concerning the second question, it is arguable whether there are effective incentives for German TSOs to deploy batteries under current regulation – even if this could reduce their needs for real-time balancing interventions and thereby could reduce the overall costs for operating the system. The reason for this doubt is that the German

TSOs do not have to bear the costs for balancing the system as they bill the transmission grid users causing imbalances for the balancing power costs (§ 8 Stromnetzzugangsverordnung) and as they are allowed to add further costs for securing the system stability to the grid fees (Bundesnetzagentur, 2014). The only incentive for TSOs to keep balancing costs low (e.g. by the deployment of batteries) stem from a voluntary self-commitment (ibid.).

Practice and future plans

There are so far no batteries used as network assets by TSOs in Germany and no corresponding announcements for the future. However, the Italian TSO, Terna, already tests batteries as elements of its grid (Terna, 2015). Terna also has plans to install further batteries for grid operation (ENTSO-E, 2014). This indicates that it could be technologically reasonable for TSOs to use batteries for operating the electricity system.

Externalities and recommendation

If net-cost reductions in the operation of the electricity network can be achieved by the deployment of batteries as network assets, this can be interpreted as beneficial from a system perspective. However, as argued, the incentives for German TSOs to use batteries to reduce the overall system costs are limited to the properties of a voluntary self-commitment. In the possible case that the incentive induced by the self-commitment to lower the system costs is financially not equivalent but smaller compared to the overall cost reductions that TSOs could achieve by using batteries, there is a positive external effect linked to the batteries. Such an effect would lead to an underinvestment in such batteries compared to what would be optimal from a system perspective. Hence, I recommend adjusting the present regulation scheme such that potential system cost reductions which could be achieved by batteries as network assets should be passed on to the investing TSOs.

3.2 Batteries of independent operators

In a second scenario, batteries could be owned and operated by independent operators for intertemporal price arbitrage on the spot markets, especially on the intraday market. This is e.g. mentioned by Wasowicz et al. (2012), Höfling et al. (2014), and Pape et al.

(2014). As the spot markets consider the German electricity system to be a copperplate, there are no price signals for where batteries used for intraday market arbitrage should be positioned. Thus, the batteries would be located anywhere in the system independent of spot market considerations.

The economic rationale of independent battery operators using intraday market arbitrage is intuitively understandable: The revenues coming from the arbitrage (buying and charging at low or even negative prices and reselling and discharging at high prices) must be greater than the batteries' LCC.

Key institutions

The design of the intraday market is a key institutional factor for the chances of success of the depicted business model of independent battery operators. In principle, independent battery operators can already participate on the German intraday market (Drake et al., 2013).

Practice and future plans

There are so far no independent battery operators in Germany trading electricity on the spot markets. However, a number of initial research and demonstration projects have been announced that want to test an independent operation of batteries on the spot markets (RWTH Aachen University, 2014).

Externalities and recommendation

If independent battery operators were trading on the intraday market, the market coordination would improve in so far as the short-term balancing of demand and supply could be enhanced because batteries can deliver – in contrast to intermittent RES – power very reliably in the short-term (Rundel et al., 2013). Therefore, the batteries could level out the intermittent feed-in of RES and thereby reduce the need for expansive real-time balancing interventions by TSOs. In this sense, the whole electricity system could benefit from independent battery operators.

However, as the spot market prices in general reflect the balancing needs of the electricity system, the independent battery operators could financially benefit from a system supporting battery operation. Thus, there exist in principle in terms of the batteries' real-time balancing benefits no positive external effects. However, to further increase the potential real-time balancing benefits of batteries independently operated on the intraday market, it may be worthwhile to consider changing the design of the intraday market such that it becomes possible, according to the technically feasible very fast reaction times of batteries, to trade power even more in the short-run – and not as today only up to 30 minutes before the delivery date.

3.3 Batteries directly connected with (large-scale) RES facilities

Batteries could also be used in direct locational and operational connection to the production of electricity by wind power and solar power[3]. This is e.g. discussed by Borhan et al. (2013), Sterrer and Prüggler (2013), Thomas and Altrock (2013), Ying et al. (2013), Jannati et al. (2014), Sarrias-Mena et al. (2014), and Ayodele and Ogunjuyigbe (2015). In this scenario, the batteries could be owned and operated by the same entities owning and operating the related renewable energy facilities or alternatively by partner operators.

The general economic decision rule for the operation of batteries in combination with an RES facility is the following: The additional revenues of the RES facility that can be generated by operating it with a battery must be higher than the LCC of the battery. Such additional revenues of RES facilities could come from the possibilities to exploit price spreads on the spot markets, especially on the intraday market, and to participate with stored electricity produced by the RES facility on the balancing power markets (primary control, secondary control, minute reserve markets).

Key institutions

The support policy for RES is in Germany mainly regulated by the Renewable Energy Act (EEG). Therefore, this is a key institution for the question of whether RES facilities could benefit from the deployment of batteries.

Owing to the guaranteed EEG feed-in tariffs being paid independently from the time when the electricity was fed into the system and lying above spot market prices, operators of RES facilities did not have any incentive to deploy batteries for time-shifting purposes on the electricity markets in the past. However, since the EEG was

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[3] The use of batteries in connection with residential PV is discussed separately in section 3.4. Batteries could also be operated in connection with biomass and hydropower. However, as these technologies will in future only play a minor role in Germany, they are not further considered in this paper.

reformed in 2014, guaranteed feed-in tariffs are now only exceptionally granted for new RES facilities if they are very small (e.g. residential PV systems). Larger new RES facilities (like wind turbines) are now supported by a certain market premium system that provides incentives for RES facilities to trade their electricity according to the scarcity signals of the spot market prices. The EEG guarantees the market premium also if the traded electricity was previously stored in a battery. Thus, the present support scheme for RES facilities in Germany provides the institutional prerequisite that the deployment of batteries in direct connection with new (large) RES facilities could be economically beneficial as it stimulates exploitation of market price spreads by shifting the feed-in. In this respect, the same behavior is rational for RES facility operators as it is for independent battery operators. However, RES facility operators storing only the electricity from their RES facilities may be less flexible than independent battery operators as they can merely charge their batteries if their RES facilities are in fact producing electricity. On the other hand, RES facility operators running batteries may have some information advantages against independent battery operators as they could interpret the production trends of their own facilities as indicators for the short-run development of the intraday market.

From 2017 onwards the financial support for all new RES facilities in Germany will be determined by a competitive bidding system. Such a system has already been in place for new freestanding solar parks since 2015. With such a support scheme, potential RES facility operators trading their electricity on the intraday market would also have an incentive to deploy batteries if this could decrease their overall costs, because potential operators of RES facilities using batteries could then realize a project with lower support payments what would help them to improve their competitive position and win the bidding for a project.

Concerning the institutional situation with respect to the balancing markets, it can be stated that battery operators are today only partially able to trade on these markets in Germany. They can operate on the primary control market but due to some technical prequalification requirements not on the secondary control and minute reserve markets (Benger et al., 2013).

Practice and future plans

So far, there are a few batteries operated in connection with RES facilities in Germany. One battery (1.6MW/1.9MWh) is for instance operated in connection with a freestanding solar park in Alt Daber, Brandenburg, providing balancing power (Schramm, 2014). In Feldheim, Brandenburg, a battery (10MW/5MWh) is operated in connection with a wind power plant also providing balancing power (Stoller, 2014). And in Braderup, Schleswig-Holstein, a battery (2.3MW/3MWh) is used in connection with a wind power plant trading on the balancing power and spot markets (Bosch, 2014).

Externalities and recommendations

If operators of RES facilities were using batteries to sell their electricity at high spot market prices, the reliability and market integration of the feed-in by the related RES facilities would increase. Thereby, the need for expensive real-time balancing interventions by TSOs could be reduced as the market prices in general reflect the system's requirements of balancing demand and supply. However, a positive external effect would not be present in this respect because the battery operators could directly benefit from their contribution to the system by benefiting from the market prices. So the only recommendation I want to make here again (see also section 3.2) is to shorten the time up to which electricity can be traded on the intraday market so that the very quick reaction times of batteries could be used more advantageously.

If an RES facility operator deploys a battery to participate on the balancing markets this implies that the fraction of electricity from its RES facility being randomly fed into the electricity system depending on the natural sun and wind conditions decreases. Consequently, also the needs for interventions by TSOs for real-time balancing caused by intermittent RES feed-in would decrease. Although the battery operators may attain higher profits providing their electricity on the balancing markets than on the spot markets, the battery operators would not explicitly financially benefit from supporting the system by relieving it from intermittent RES feed-in. Thus, there would be a positive external effect in this respect. Therefore, I recommend that RES facility operators that store some of their produced electricity to trade it on the balancing markets should get a premium by the TSOs. Moreover consideration should be given, as also suggested by other commentators (e.g. Wasowicz et al., 2012), to adjusting the prequalification requirements of the balancing markets such that – as far as this is technically feasible – electricity from batteries can also be traded on the secondary control and minute reserve markets. This could relieve the spot markets from even more intermittent RES feed-in and could simultaneously increase competition on the balancing markets, which could lead to lower balancing power prices and thereby eventually also to lower system costs.

3.4 Batteries in buildings combined with PV

Batteries could also be used in a decentralized manner in residential or commercial buildings in connection with PV systems. This is discussed for example by Toledo et al. (2010), Bruch and Müller (2014), Hoppmann et al. (2014), Weniger et al. (2014), Agnew and Dargusch (2015), and Luthander et al. (2015). The batteries could be owned and operated by the same entities owning and operating the corresponding PV systems.

The economic rationale for PV battery owners can be to maximize the self-consumption of their own PV system if the generation costs of the PV power including the LCC of the battery are lower than the alternative costs for purchasing equivalent power on the retail market. Furthermore, these cost savings must be higher than the alternative profit of the PV system that could be obtained if it were operated without a battery.

Key institutions

One key institution for PV battery systems is the support policy for PV power, which is determined in Germany by the Renewable Energy Act (EEG). Owing to relatively high guaranteed feed-in tariffs, it has been in the past economically more attractive for PV system owners in Germany to feed their electricity directly into the grid than to deploy batteries for increasing self-consumption (Weniger et al., 2014). However, in recent years the feed-in tariffs for PV power decreased significantly and the retail prices for private households increased sharply – from 2000 to 2014 by more than 90 percent (Statistisches Bundesamt, 2014). In connection with improvements of the battery storage technology and declining costs of batteries, this has led to the situation that batteries for small PV systems enabling increased self-consumption can already today be economically reasonable (Hoppmann et al., 2014).

Further institutional arrangements that influence the profitability of PV battery systems include in particular the regulations concerning possible exemptions for such systems from obligations to pay electricity taxes, the renewable energy levy, and grid fees. Moreover investment subsidies also play a considerable institutional role for the diffusion of PV battery systems. In Germany, the national development bank (KfW) provides low-interest loans and repayment subsidies for investments into PV battery systems (KfW, 2015).

Practice and future plans

There are various companies in Germany selling PV battery systems. According to the German association of the solar industry, the demand for such systems is strongly increasing and by the beginning of 2015, already more than 15,000 households in Germany were operating PV battery systems (BSW Solar, 2015). Most of the available systems have capacities in the range of 1-50kWh and a maximum discharge power of 1-20kW (pv magazine, 2014).

Externalities and recommendation

PV battery systems are not per se advantageous for the operation of the electricity system (Benger et al., 2013; Wittwer, 2013; Waffenschmidt, 2014). If the battery of a PV system is for instance already fully charged before noon, the need for interventions by TSOs in terms of real-time balancing will not be reduced as the intermittent PV peak will still be completely fed into the grid – as in the case without batteries. However, a grid supporting dimensioning and operation of PV battery systems is possible (Benger et al., 2013; Hollinger et al., 2013). The KfW support program for PV battery systems takes this into account. It is only granted to PV battery projects that fulfill certain specifications ensuring a grid supporting operation (KfW, 2015). This implies that grid supporting contributions of PV battery systems are financially rewarded by the KfW program. Hence, in this sense there is no positive external effect in terms of the grid support of PV battery systems. Therefore, my policy recommendation in this respect is to retain the status quo.

	Batteries as network assets	***Independent Batteries***	***Batteries for RES facilities***	***Home batteries for PV***
Location of the batteries	Within the grid at places allowing support of transmission services	Anywhere depending on considerations not related to electricity markets	Directly connected to (large-scale) RES facilities	In commercial or residential buildings with PV
Ownership and operation	TSOs	Independent battery operators	Owners and operators of RES facilities or third party cooperation partners	Owners and operators of the PV facilities
Conceivable economic rationales	Cost savings for real-time balancing interventions	Price arbitrage on the spot markets (especially on the intraday market)	Exploitation of spot market price spreads (especially on the intraday market) and/or participation in the balancing markets	Cost savings through the maximization of self-consumption (reduced retail market purchases)
Key institutions considered	Regulation of the electricity sector	Designs of the intraday market	German support policy for RES: Renewable Energy Act (EEG)	German support policy for RES: Renewable Energies Act (EEG) Tax exemptions etc. Public investment subsidies (KfW program)
Status of these key institutions	Deployment of batteries possible but incentives for TSOs to do so in order to lower real-time balancing costs only arise due to a voluntary self-commitment	Intraday market: trading possible	Depicted use of batteries possible (Balancing markets: trading only possible on primary control market)	Allow and encourage the depicted use of batteries
Practice in Germany	No projects (a few in Italy)	Only some initial R&D projects planned	A few batteries in use (some even without subsidies)	15,000 PV battery storage systems already in use
System benefits in terms of real-time balancing	Possible due to potential cost-savings for real-time balancing interventions	Intraday trading: Yes (due to an improvement of the markets making fewer real-time balancing interventions necessary)	Intraday trading: Yes (due to a more flexible, reliable and market integrated feed-in of RES facilities) Balancing market trading: Yes (due to a reduction of the intermittent RES feed-in and decreasing costs for balancing power)	Not per se beneficial, but a system supporting configuration and operation of batteries is possible
Positive externalities of the batteries in terms of real-time balancing	Yes (given that the voluntary self-commitment doesn't induce adequate incentives for TSOs to lower real-time balancing costs)	No (on the basis that market prices reflect the balancing needs of the system)	No in the case of spot market trading (on the basis that the prices reflect the balancing needs of the system) Yes in the case of balancing market trading (because the reduction of intermittent RES feed-in is not rewarded)	No (because grid supporting PV battery systems are subsidized by a KfW program)
Recommendations	Adjust the regulation such that TSOs could adequately benefit from cost reductions for real-time balancing	Allow more short-term intraday trading (<30min)	Allow more short-term intraday trading (<30min) Allow batteries to trade on all balancing markets as far as this is technically possible Enable premium for trading on balancing markets	None

Table 1: Summary of the results

4 Conclusion

Considering four fundamental options for the location of battery storage systems, I outlined different business models. I identified key institutions influencing the diffusion of these models in Germany. I considered whether the battery storage options would bring benefits for the electricity system in terms of its real-time balancing needs. Finally, I analyzed which of the battery storage system options might be associated with positive external effects with respect to the system's real-time balancing needs and I made suggestions for how the identified externalities could be internalized.

Namely, I considered the following four battery storage options: (1) Batteries operated by TSOs as network assets, (2) batteries of independent operators operated on the intraday market, (3) batteries directly connected to (large-scale) RES facilities used for intraday or balancing market trading, and (4) batteries in buildings connected to PV systems aimed at maximizing self-consumption.

The analysis demonstrated that, although all four considered battery storage options can bring benefits for the electricity system in terms of its real-time balancing needs, these benefits do not necessarily include financial reward for all the battery operators. Such positive externalities were identified for batteries operated by TSOs as network assets and for batteries connected to RES facilities operating on the primary control market. For these cases, I recommend institutional reform to enable the internalization of the positive externalities, thereby enhancing economic efficiency from a system perspective. Namely, I suggest an adjustment of the incentive regulation such that TSOs are able to benefit financially from system cost reductions which they can potentially realize through the deployment of batteries. I also recommend the introduction of a premium for RES facilities trading stored RES electricity on the balancing markets such that RES facilities receive compensation for reducing intermittent RES power feed-in, which would otherwise increase system stress. Moreover, I argue – apart from the discussion on externalities – that further system supporting potential of battery storage systems could be tapped by institutional changes to the intraday market (allowing more short-term trading) and to the balancing markets (allowing batteries also on the secondary control and minute reserve markets).

The considerations in this paper might be of value because they contribute to the emerging field of battery storage literature by applying a system perspective including basic technical and institutional considerations with respect to the idea of externalities and economic efficiency. Such an approach seems reasonable as the electricity system is multi-dimensional and calls for integrated considerations not restricted to technical, economical, legal, or other aspects.

However, the insights of this paper are to some extent limited because it only takes a qualitative reasoning approach. For instance, it would be interesting to quantify the identified externalities. This is for instance relevant for the determination of the appropriate value of the suggested premium for RES facility operators trading electricity stored with batteries on the balancing markets.

Future research could also expand the analysis of battery storage systems to their effects concerning grid extensions, congestion management and further ancillary services like black start capability. Multi-functional operational modes of batteries should explicitly be taken into account for this. Furthermore, it should be borne in mind that the implicit assumption in this paper that battery operators are only price takers may no longer be reasonable to the extent that a significant capacity expansion of batteries occurs. In addition, environmental externalities of batteries should be considered in continuing studies. Future research on externalities could also study further siting options and business models of battery storage, other storage technologies (e.g. compressed air energy storage) and other flexibility options (like demand-side-management). Finally, this could lead to recommendations concerning how the institutional framework for the electricity sector could be revised, with a view to enabling economically efficient options and outcomes.

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Electricity storage operation under different cost and market structures

Paul Neetzow*

Abstract

The significance of electricity storage for a transition to $\mathrm{CO_2}$-neutral power production is broadly accepted. Yet, no consent exists about the optimal deployment amount depending on the share of intermittent renewable energies (RE). Employing a simple but new model, the market outcome for storage installation in a monopolistic market with no storage costs and in a competitive market with energy and power capacity costs is computed. The storage exploits arbitrage potential from the difference in power prices.

The model results indicate that substantially more storage capacity (power and energy) is installed in a competitive market compared to the monopolistic case. For linearly rising marginal production costs of power generation the deployed energy and power storage does only negatively depend on the installation costs as well as mostly positively on the demand difference between peak and off-peak times. However, with quadratic marginal cost structure the storage capacities rise additionally with the magnitude of the load demand. As increases of RE lead to a higher peak/off-peak difference and a decrease of load magnitude, the effects on storage are opposing. Empirical data may be used to identify the dominant effect.

Keywords: power, energy, capacity, efficient storage deployment, competitive market

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*Email-address: pneetzow@outlook.com; Carl von Ossietzky University Oldenburg, Germany

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1 Introduction

The European Union has set ambitious CO_2-reduction targets, especially concerning the power production sector. By 2050 electricity generation is supposed to be quasi climate neutral. In Germany 80 % of electricity production are supposed to be generated by renewable energies (RE) by that time with nuclear power production fully abandoned. However, with the exception of biomass, recent technologies are intermittent and restricted in their locations as well as hardly predictable in their generation (Crampes and Moreaux, 2010). Large areas (solar, biomass) or suitable locations (wind) are required, what leads to rising marginal installation costs. On the other hand, electricity demand is also seasonally (Barton and Infield, 2004) and statistically (short term) volatile (Growitsch and Weber, 2008). Further it is barely price elastic concerning its time as well as its location (Kirschen, 2003). Even though the temporal inelasticity may potentially be somewhat reduced by demand side management (Kirschen, 2003; Strbac, 2008), a supply-demand-discrepancy that must be overcome will remain or enhance for time and space, especially with rising shares of renewable energies (Steffen and Weber, 2013).

Furthermore electricity was in the past considered a basically non-storable commodity (Chao, 1983). Both shortage and oversupply were therefore problematic in terms of supply stability and quality. However, in recent years there exist a growing number of storage technologies with different cost structures, capacities etc. (e.g. pumped hydro, compressed air, battery) that allow to transfer the electricity supply in time. Thereby peak load shaving may be achieved, leading to production cost savings as flexible high cost plants may be substituted (Chen et al., 2009). Of course this raises demand in low consumption (off peak) times when the storages are recharged.

To address different aspects of electricity markets modeling approaches have been commonly used. For example, Nguyen (1976) introduces a simple model to address peak load pricing with storage. Gravelle (1976) uses a more comprehensive model to approach questions concerning optimal storage, and its influence on prices and the capacity of the regular power plant park. Further work has for example addressed the determinants of electricity prices (Girish and Vijayalakshmi, 2013), welfare effects of ownership structure (Sioshansi, 2010), and the effect of storage on electricity shadow prices, production costs and wholesale prices (Nyamdash and Denny, 2013). Steffen and Weber (2013) give a detailed analysis of storage behavior against the background of increased shares of RE.

Like the works cited above, the here presented paper uses a mathematical modeling approach. It picks up questions concerning efficient storage installation and operation raised by Gravelle (1976). However, the models differ significantly. For example a continuous time frame is used here rather than discrete instants. We aim to evaluate the storage operation under different cost structures, as well as to analyze, how a change of the residual load curve, especially induced by rising shares or RE power production, effects the deployment of electricity storage. Therefore different market and cost structures for the storage operation are distinguished.

The paper is structured as follows. After introducing the general features of the model, a simple reference case of cost free storage in a competitive market is computed. Yet, as real markets are imperfect, we go on analyzing a storage cost free monopolistic market set up, which allows us to evaluate some influence of the market structure. In the next steps, to increase realism, costs for storage power and energy capacity are introduced separately in a competitive market. Eventually the findings are discussed and conclusions are drawn.

2 Model

2.1 General assumptions

The modeling objective in this work is to find equilibrium solutions for storage functions $y(t,\cdot)$ (kW), which describes the over time storage operation, for competitive markets (i.e. with profit $\Pi = 0$ (\$)) with subject to different costs structures and one reference monopolistic market (i.e. $\max\limits_{y(t,\cdot)} \Pi$) without storage costs. The solutions enable to draw conclusions about the impact of storage costs, market structure and implicitly the influence of RE on the deployment of electricity storage.

The model is based on electricity price arbitrage considerations of storage operators. In general storage must compete with conventional electricity production with rising marginal costs. Storage pays if revenues from buying, when prices are low and selling when prices are high, do at least cover costs. However, the demand and supply of the storage plant do influence the market price for electricity. Hence, excessive deployment will reduce the value of the storage as the arbitrage potential decreases.

The cost-effective demand may be expressed by a residual load duration curve R (kW) as comprehensibly explained in Steffen and Weber (2013). It deducts solar and wind generation from the total electricity demand as their variable costs are close to zero. Further the load values of a certain period are sorted from highest to lowest thus yielding a strictly monotonically decreasing function. A linear function is a fair approximation for R and can simply be defined by the two parameters a (kW), which is the maximum electricity demand over the period and b ($\mathrm{kW/h}$), which is a measure for the demand amplitude:

$$R(t) = a - bt. \tag{1}$$

Note that all times t in the model are sorted with R as indicated above. The (short term) price in-elasticity is thereby a typical feature of electrical energy demand (Kirschen, 2003). No storage is considered in R. For further simplification reasons the analyzed time period is defined to be $t \in (0, 1)$. This yields the benefit of generalization for the model. The time frame is not restricted to a day, a week or a year but may be analyzed as serves the respective purpose.

Additionally, storage is introduced in the market. Along the whole period storage operators may decide whether to charge (buy) or discharge (sell). The decision may be expressed by the storage function $y \in (-K, K)$, where K (kW) is the maximum available power capacity of the plant and a positive sign denotes discharging, a negative charging. Further, the stored and discharged energy (i.e. maximum energy capacity) along one period can be derived by time integrating all discharge ($y > 0$) capacity:

$$\kappa\ (\mathrm{kWh}) = \int_{t=0}^{t=1} y\ dt,\ \forall y > 0. \tag{2}$$

It follows that storage operation will influence the necessary electricity supply of controllable plants x (kW) in a simple matter:

$$x(t) = R(t) - y(t). \tag{3}$$

As marginal costs for wind and solar are close to zero, to derive marginal production costs, one only needs to consider the rising marginal costs of the controllable plant park $p = p(x)$ (\$/kWh). Pricing takes place along the merit order of the generation plants such as the most expensive generation that is needed at a given time determines the price. Thus, as the supply rises, marginal production costs increase as well (Kirschen, 2003). In the model the pricing is approximated as

$$p(t) = x(t)^2 \text{ and } p(t) = x(t). \tag{4}$$

Note, that for $x < 0$ it should be $p < 0$, what cannot be achieved by the quadratic function. Hence, negative pricing ($p < 0$) must be eliminated and it must be $R \geq y$. Thus, a negative R must be compensated by the demand of the storage such as $\forall\ t : x(t) \geq 0$.[1] As a result, negative market prices, which may become more common with higher shares of RE (Steffen and Weber, 2013, p. 563), cannot be dealt with in the model. The influence of the storage on market prices is considered as it alters the necessary supply of controllable plants (x), thereby affecting market prices $p(x)$.

At this point the model does not contain storage losses. Hence, the charge must equal the discharge, i.e.

$$\int\limits_{t=0}^{t=1} y(t)dt = 0 \tag{5}$$

or

$$\left\{ \int_{t=0}^{t=1} y(t)dt, y > 0 \right\} = \left\{ - \int_{t=0}^{t=1} y(t)dt, y < 0 \right\}. \tag{6}$$

respectively.

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[1] For algebraic reasons only $p(t) = x(t)$ is used in section 2.2.

The yielded storage profits are

$$\Pi = \int_{t=0}^{t=1} y(t)p(t)dt - C, \tag{7}$$

where C represents the costs for storage installation and operation. Thereby it is important to emphasize that storage costs are handled such as they must be paid for in just one load cycle. As a consequence C is the sum of variable and fixed expenses per load cycle.

2.2 Storage without costs

A competitive market

It is obvious that for a cost free storage operation, every alteration of $p(t)$ and thus $x(t)$ would imply a potential for arbitrage. In other words, if there was a price differential between any two points in time, a storage provider operating with zero costs ($C = 0$) could exploit that difference and make a profit. However, in a competitive market it must be $\Pi = 0$. From this it follows that $p(t)$ and $x(t)$ must be constant over time. Equation 5 does hence yield

$$x(t) = a - \frac{b}{2}. \tag{8}$$

Inserting into equation 3 yields the storage function as

$$y(t) = \frac{b}{2} - bt. \tag{9}$$

From equation 5 it is easy to compute that for $t \in (0, 0.5)$ the storage will be discharged and for $t \in (0.5, 1)$ it will be charged. The deployed power and energy capacities are $K = max(y) = b/2$ and $\kappa = b/8$ (derived from equation 2).

A monopolistic market

Analyzing different market structures enables to draw conclusions about some institutional effects on the results. As new storages are only slowly deployed in the moment and they are also locally restricted (e.g. due to transmission constraints, which we do not consider here) a perfectly competitive market is far from realistic. To analyze some implications of the competitive market simplification that is made later, we will compare the results to a monopolistic set up. Surely real world values will be somewhere between these extreme results and depend on the degree of market competitiveness.

To derive the optimal storage function $y(\cdot)$ one has to solve the following dynamic optimal control problem with the binding constraints of equation 3 and 5:

$$\max_{y(\cdot)} \Pi = \int_0^1 y(t)p(t)dt \tag{10}$$

s.t.

$$x(t) = R(t) - y(t) \tag{3}$$

$$\int_0^1 y(t)dt = 0 \tag{5}$$

Further as implied by equation 2 the change of storage must equal the (dis)charge $y(t)$ at the time. Thus, it is

$$\dot{\kappa}(t) = y(t). \tag{11}$$

As loads are time sorted (max$(R(t)) = R(t = 0)$) and the highest discharge max$(y(t))$ will take place simultaneously with the maximum of the residual load duration curve (max(R)), it is implied that

$$\max(y(t)) = y(t = 0) \equiv K. \tag{12}$$

The Hamiltonian is to be set up as follows in the simple case of linearly rising marginal costs $p(t) = x(t)$:[2]

$$H = y(t)(R(t) - y(t)) + \lambda y(t). \tag{13}$$

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[2] For the more advanced case of $p(t) = x(t)^2$, the algebra of the optimization problem becomes disproportionally hard to solve.

To solve the above problem one may set

$$0 = \frac{dH}{dy} = R - 2y + \lambda \tag{14}$$

$$\dot{\lambda} = -\frac{dH}{d\kappa} = 0 \tag{15}$$

thus λ must be constant and we can write:

$$y(t) = \frac{R+\lambda}{2} \tag{16}$$

$$\lambda = \lambda_0. \tag{17}$$

From the above equations 5 and 16 it must hold that

$$\int_0^1 \frac{R+\lambda_0}{2}\, dt = 0 \tag{18}$$

and thus

$$\lambda_0 = \frac{b}{2} - a. \tag{19}$$

From the equations 12, 16, 17 and 19 we find the solutions

$$y(t) = \frac{b}{4} - \frac{b}{2}t = K - \frac{b}{2}t \tag{20}$$

$$x(t) = a - K - \frac{b}{2}t. \tag{21}$$

From equation 5 it is again easy to see that for $t \in (0, 0.5)$ the storage will be discharged and for $t \in (0.5, 1)$ it will be charged. The maximum profit to be derived is

$$\Pi = \int_0^1 y(t)x(t)dt = \frac{b^2}{48}. \tag{22}$$

The maximum profit for $p(t) = x(t)^2$ using the above results for $x(t)$ and $y(t)$ is[3]

$$\Pi = \int_0^1 y(t)x(t)^2 dt = \frac{b^2}{48}(2a - b). \tag{23}$$

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[3] Of course this is only an approximation as the optimization assumes $p = x$.

The deployed capacity is thus $K = b/4$, the discharged energy, derived from equation 2 and 20, amounts for $\kappa = b/16$. K and κ do not depend on the maximum load a.[4] However, the greater the slope (i.e. b) of R, the more arbitrage may be made and the more storage will be profitable, which is indeed an intuitive result.

2.3 A competitive market with storage costs

Power capacity costs

Consider total storage costs as a function only of the installed storage power $C = \eta K$ (\$). For simplicity reasons energy capacity costs are neglected. It is obvious that once power capacity is installed (and paid for), a competitive market will yield the same outcome as in the case of no costs (i.e. a full load leveling). This will be the case if $K \geq |R - x|$. On the other hand, storage utilization will be maximized (i.e. $y = K, -K$) as long as $K \leq |R - x|$. In this period the operator will be able to generate a revenue to pay for the installation of K as buying and selling prices $p(t) = x(t)^2$ diverge. We define the times t_1 and t_2 such as $\forall t \in (t_1, t_2) : K \geq |R - x|$ (figure 1). From the competitive outcome with no costs (equation 9) we conclude that

$$x(t_1) = R(t_1) - K = a - b/2, \tag{24}$$

$$x(t_2) = R(t_2) + K = a - b/2. \tag{25}$$

As charging must equal discharging (equation 5), it can be shown that $t_2 = 1 - t_1$. Further, as $x(t_1 \leq t \leq t_2)$ is constant, equation 1 and 24 yield $y(t_1 \leq t \leq t_2) = K(1 + \frac{t - t_1}{t_1 - 0.5})$.

Summarizing, we find that:

$$\begin{cases} \text{for } t \in (0, t_1) & : y = K, \\ \text{for } t \in (t_1, 1 - t_1) & : y = K(1 + \frac{t - t_1}{t_1 - 0.5}), \\ \text{for } t \in (1 - t_1, 1) & : y = -K. \end{cases}$$

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[4] Even though this may changes for non-linear pricing i.e. $p = x^2$.

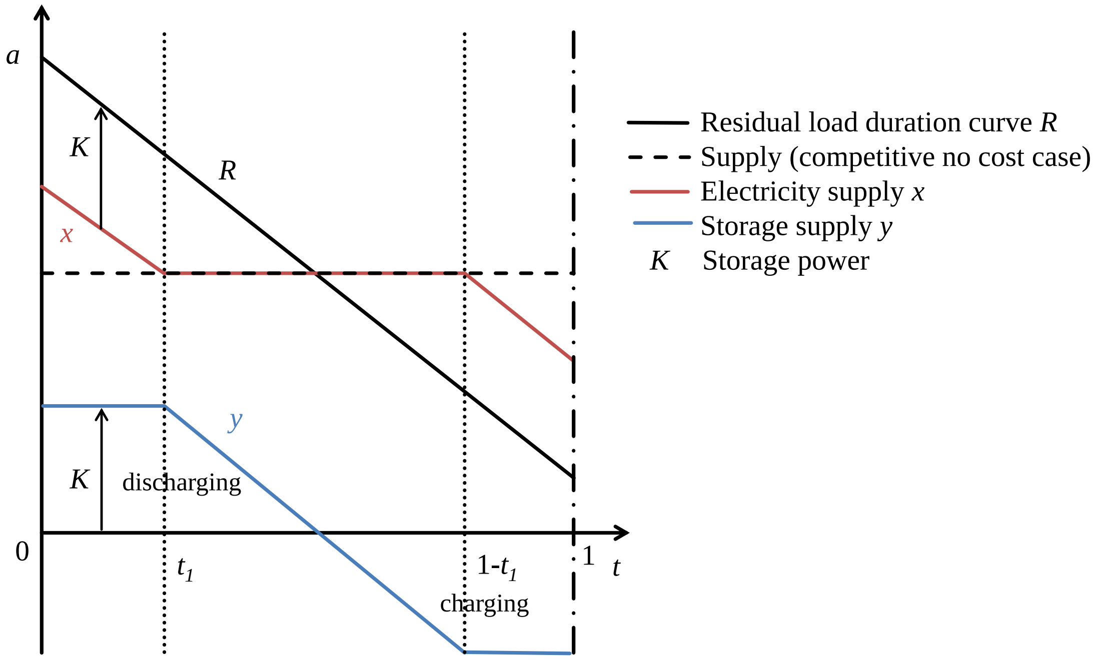

Figure 1: Storage function y and regular electricity supply x compared to the constant supply from the competitive no cost case (section 2.2). Storage runs on full power ($y = R - x = \{K, -K\}$) as long as $K \leq |R - x|$ and results in load leveling ($x = a - b/2, \forall t \in (t_1, 1 - t_1)$) otherwise.

Inserting in equation 1 results in:

$$\begin{cases} \text{for } t \in (0, t_1) & : x = a - K - bt, \\ \text{for } t \in (t_1, 1 - t_1) & : x = a - \frac{b}{2}, \\ \text{for } t \in (1 - t_1, 1) & : x = a + K - bt. \end{cases}$$

The profit condition (equation 7) can than be rewritten for a competitive market as

$$\Pi = \int_0^{t_1} K(a - K - bt)^2 dt + \int_{t_1}^{1-t_1} (a - \frac{b}{2})^2 K(1 + \frac{t - t_1}{t_1 - 0.5}) dt + \int_{1-t_1}^{1} -K(a + K - bt)^2 dt + C = 0. \tag{26}$$

As defined earlier for $t \in (t_1, 1 - t_1)$ revenues must be zero, which can also be shown by solving:

$$\int_{t_1}^{1-t_1} (a - \frac{b}{2})^2 K(1 + \frac{t - t_1}{t_1 - 0.5}) dt = 0. \tag{27}$$

Further, as it is

$$x(t_1) = a - K - bt_1 = a - \frac{b}{2}, \tag{28}$$

it must hold that

$$t_1 = \frac{1}{2} - \frac{K}{b}. \tag{29}$$

Inserting equations 29 and 27 in equation 26 allows to solve for K deriving:

$$K = \left\{ 0,\ \frac{b}{2} \pm \frac{\sqrt{2a\eta b - \eta b^2}}{2a - b} \right\} \tag{30}$$

$K = 0$ is an apparent but uninteresting solution, as no storage must yield $\Pi = 0$. In fact, the proper solution is

$$K = \frac{b}{2} - \frac{\sqrt{(2ab - b^2)\eta}}{2a - b}, \tag{31}$$

as the summation does also yield $\Pi = 0$, however, $K > b/2$ does not make sense as the resulting x would overshoot the competitive no cost solution of total load leveling (compare equation 9). Setting $K = 0$ yields the choke price (\$/kW).

$$\eta_{cp} = \frac{1}{4}(2ab - b^2), \tag{32}$$

If capacity installation will be more or equally expensive ($\eta \geq \eta_{cp}$), no storage will be deployed.

Due to the quadratic nature of the cost function, no negative prices can be realized. Thus, it must be avoided that $x < 0$. Therefore, from equations 1 and 3 we may write $K \geq bt - a$.[5] Due to the time sorting, x will be lowest at $t = 1$. Therefore the condition

$$K \geq b - a \tag{33}$$

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[5] This means that an oversupply of RE which would lead to negative prices has to be consumed by the storages such as the resulting market price $p(x)$ does not get negative.

must hold, which with equation 31 yields

$$0 \leq \eta < \frac{(2a-b)^3}{4b}. \tag{34}$$

Differentiating K with respect to b yields (for $a, b, \eta > 0$)

$$\frac{dK}{db} = \frac{1}{2} - \frac{a\eta}{(2a-b)^{3/2}\sqrt{b\eta}} \tag{35}$$

Hence for realistic values of $a > 0$ and $0 < b < 2a$ it will be $dK/db > 0$ in the case of

$$0 \leq \eta \frac{b(2a-b)^3}{4a^2}. \tag{36}$$

Comparing the two conditions for η (equations 34 and 36) shows that the latter is more restrictive for $a < b$ and vice versa. From that it follows, that under the assumptions made, a rise in the demand amplitude (b) will always be accompanied by an increasing storage power K as long as $x \geq 0$ (i.e. $\forall t : K \geq bt - a$). Figure 2 visualizes these findings for some values of η in the special case of $a = 1$.

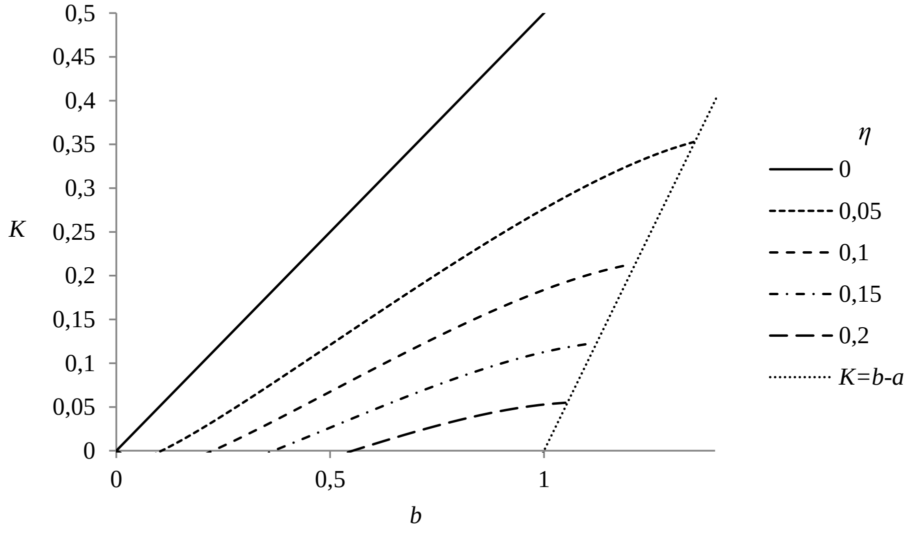

Figure 2: Solution for storage power capacity K over b in the case of $a = 1$ and different capacity costs η. With rising b also K does increase. Functions are restricted by the condition in equation 33.

Further (for $a, b, \eta > 0$) it is

$$\frac{dK}{da} = \frac{\sqrt{b\eta}}{(2a-b)^{3/2}} \tag{37}$$

As $2a > b$ it is obvious that $dK/da > 0$. Hence a rise in the maximum demand (a) will also lead to an increase in storage capacity installation (K).

Steffen and Weber (2013) and Schill (2014) point out that increasing shares of RE will result in a slight downward shift (i.e. decreasing a) and a steepening (i.e. increasing b) of the residual load duration curve, as the supply of wind and solar is deducted from the total demand to derive R and from the higher influence of volatile RE in the total electricity supply. Hence, both effects oppose each other in terms of the change in K. The dominant effect can be found by putting the derivatives into proportion:

$$\frac{dK}{db}\frac{da}{dK} = \frac{(2a-b)^{2/3}}{2\sqrt{b\eta}} - \frac{a}{b}. \tag{38}$$

To draw conclusions on the final implications for the storage power capacity, a more comprehensive analysis is needed to quantify this equation. At this point it gets important to decide on a time frame for t and to use empirical data for a and b as well as to access quantified information on the impacts of rising RE on R.

Yet, it is worth noticing that with little adjustment of equation 31 it can be shown that the effect of the change in a strongly depends on the characteristics of the cost function $p(x,t)$. E.g. a linear function $p(t) = x(t)$ does lead to

$$K = b/2 - \sqrt{\eta b} \tag{39}$$

and thus to $dK/da = 0$ and $dK/db > 0$ for all cases where storage is deployed. An increasing share of RE will hence lead to a rising storage amount with power costs.

Energy capacity costs

Let us assume the total (dis)charged energy capacity κ (equation 2) along one time period must be installed. Thereby it is neglected that storage energy may be used more than once within one period. This assumption is discussed at the end of this section. Total storage costs are a function of the installed energy capacity $C = \nu\kappa$, where ν denotes the costs per energy ($\$/\mathrm{kWh}$).

Under any market structure an additional quantity may only be provided if it can at least cover its costs. Let us assume that the maximum price to sell is p_0, the minimum price to buy is p_2. The operator decides to install a marginal amount of capacity $d\kappa$ to use the arbitrage potential of the price differential $p_0 - p_2$ only in case it can yield an additional (marginal) profit $d\Pi$, thereby considering installation costs $\nu d\kappa$:

$$d\Pi = d\kappa\,(p_0 - p_2) - \nu\; d\kappa. \tag{40}$$

The competitive market outcome requires $d\Pi/d\kappa = 0$. Hence, we find

$$\frac{d\Pi}{d\kappa} = 0 = (p_0 - p_2) - \nu. \tag{41}$$

Obviously, a distinct price differential is derived. For $p_0 - p_2 > \nu$, an additional storage deployment will always be viable, whereas for $p_0 - p_2 \leq \nu$, no more storage will be installed. This implies a constant price plateau and a constant price valley along the time period. We define t_1 such as $\forall t \in (0, t_1) : p = p_0$ and t_2 such as $\forall t \in (t_2, 1) : p = p_2$. From equation 4 a constant price is only possible with an equally constant electricity supply x at that time. This induces peak shaving of x with the steady plateaus x_0 and x_2, whereas for $p \in (p_0, p_2)$ or likewise for $t \in (t_1, t_2)$, no storage will be operated (figure 3). This may be summarized as follows:

$$\begin{cases} \text{for } t \in (0, t_1) & : x(t)_{discharge} = x_0, \\ \text{for } t \in (t_1, t_2) & : x(t) = R(t), \\ \text{for } t \in (t_2, 1) & : x(t)_{charge} = x_2. \end{cases}$$

From the equations 4 and 41 we can conclude that

$$\nu = x_0^2 - x_2^2. \tag{42}$$

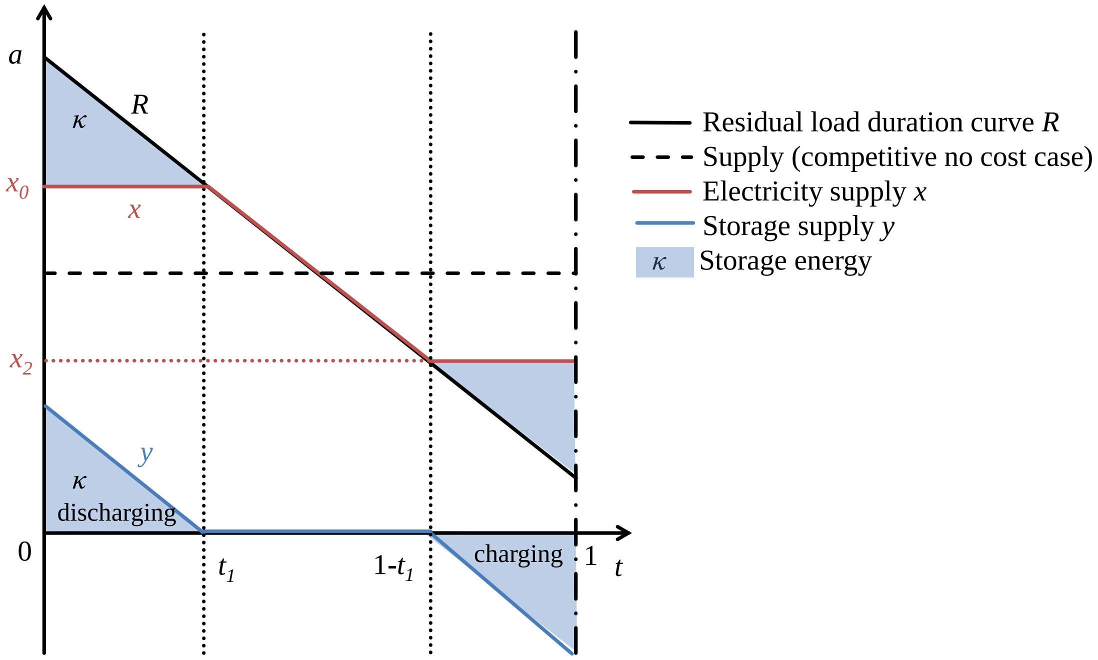

Figure 3: Storage function y and electricity supply x compared to the constant supply of the competitive no cost case (section 2.2). Installed storage κ will result in peak shaving. Between the plateaus for $t \in (t_1, t_2)$ operation is non-viable leading to $y = 0$.

Under these circumstances equation 5 results in $t_1 = 1 - t_2$. Furthermore, it must be

$$a - \frac{b}{2} = \frac{x_0 + x_2}{2}. \tag{43}$$

Thus we find

$$x_0 = a - \frac{b}{2} + \frac{\nu}{4a - 2b}, \tag{44}$$

$$x_2 = a - \frac{b}{2} - \frac{\nu}{4a - 2b}. \tag{45}$$

As $\forall t : x \geq 0$, it must hold that

$$\nu \leq (2a - b)^2 . \tag{46}$$

Inserting in equation 3 yields

$$
\begin{cases}
\text{for } t \in (0, t_1) & : y = \frac{b}{2} - \frac{\nu}{4a-2b} - bt, \\
\text{for } t \in (t_1, 1-t_1) & : y = 0, \\
\text{for } t \in (1-t_1, 1) & : y = \frac{b}{2} + \frac{\nu}{4a-2b} - bt
\end{cases}
$$

Looking at the intersection of x and R at $t = t_1$ and $t = t_2$, one can solve

$$t_1 = \frac{1}{2} - \frac{\nu}{4ab - 2b^2} \tag{47}$$

$$t_2 = 1 - t_1 = \frac{1}{2} + \frac{\nu}{4ab - 2b^2}. \tag{48}$$

The installed storage energy capacity κ is then found to be

$$\kappa = \int_0^{t_1} y \, dt = \frac{(2ab - b^2 - \nu)^2}{8b(2a-b)^2}. \tag{49}$$

For $\nu = 0$ the maximally installed energy capacity is found to be $\kappa = b/8$ (compare section 2.2). κ becomes zero at a choke price ($\$/\mathrm{kWh}$) of

$$\nu_{cp} = 2ab - b^2. \tag{50}$$

If storage energy installation will be more or equally expensive ($\nu \geq \nu_{cp}$), no storage will be deployed.

Further it is interesting to look at how a changing residual load duration curve affects the energy capacity. Remember that Steffen and Weber (2013) as well as Schill (2014) point out that increasing shares of RE will result in a slight downward shift (i.e. decreasing a) and a steepening (i.e. increasing b) of R. κ will react on changes in a and b as follows:

$$\frac{d\kappa}{da} = \frac{\nu(-2ab + b^2 + \nu)}{2b(b-2a)^3} > 0 \tag{51}$$

$$\frac{d\kappa}{db} = \frac{(-2ab + b^2 + \nu)(4a^2b - 4ab^2 + 2a\nu + b^3 - 3b\nu)}{8b(b-2a)^3}. \tag{52}$$

It should hold that $b \lessapprox a$ or at least $b \ll 2a$ to avoid negative pricing (compare equation

46). Therefore the denominator of equation 51 must be smaller than zero. Also with $\nu < 2ab - b^2$ i.e. ν smaller as the choke price, the numerator will also be smaller than zero as long as $b < 2a$. Thus $d\kappa/da$ must be positive in that case and an increase in a will result in an increase in κ, too.

From the above analysis we can conclude that $d\kappa/db > 0$ in case the above conditions hold and additionally $(4a^2b - 4ab^2 + 2a\nu + b^3 - 3b\nu) > 0$. This is the case

$$\begin{cases} \text{for } 0 < b < \frac{2}{3}a & : \text{if } \frac{-4a^2b+4ab^2-b^3}{2a-3b} < \nu < 2ab - b^2, \\ \text{for } \frac{2}{3}a \leq b < a & : \text{if } \nu < 2ab - b^2, \\ \text{for } a \leq b \leq 2a & : \text{if } \nu < \frac{-4a^2b+4ab^2-b^3}{2a-3b}. \end{cases}$$

One can think about combinations of low a and high b as will be the case with great amounts of deployed wind and solar production, in which an additional increase in RE will lead to a reduction of viable storage from both effects (decreasing a, increasing b, figure 4). However, under *regular* (i.e. recent) conditions the effects are opposing each other. As b is rising faster than a is falling when RE are installed (Steffen and Weber, 2013), the positive effect on storage is probably stronger. Nevertheless, a more evaluated analysis is desirable to give certainty.

For the simpler case of linearly rising marginal costs of power plant production ($p = x$), it is easy to show that equation 42 simplifies to $\nu = x_0 - x_2$. Eventually this will result in

$$\kappa = \frac{(b - \nu)^2}{8b} \tag{53}$$

and hence it is $d\kappa/da = 0$ and $d\kappa/db > 0$ in all cases where storage is deployed. For a rising share of RE, storage installation is also increased.

Computing the model with the time sorted residual load duration curve raises some significant restrictions for the analysis of the optimal storage energy κ. The solution might be heavily distorted by volatility along the considered time period i.e. deployed storage energy may be used multiple times without additional costs. In that case it will be worthy to increase storage operation exceeding the derived $y(t)$. Especially y is probably increased at the times with low price differences (arbitrage potential), where

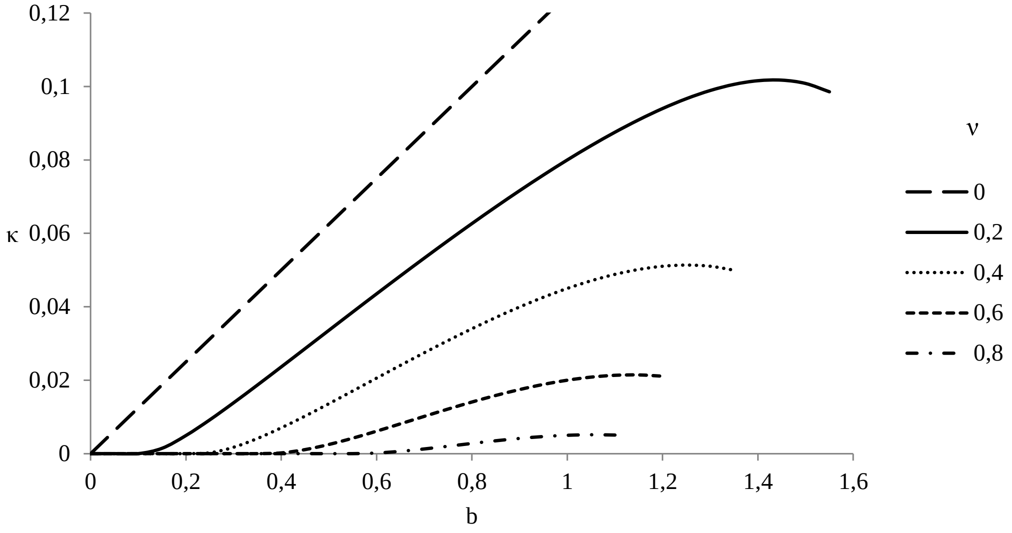

Figure 4: Energy capacity κ as a function of b and for different ν for $a = 1$. Under *regular* conditions (i.e. $b \lessapprox a$) a rise in b increases κ. Only for a large b may the effect be reversed. Functions begin to rise after overcoming the choke price (i.e. $\nu < 2ab - b^2$) and are cut off at high bs by the restriction forbidding negative pricing ($p \geq 0$, compare equation 46).

an additional storage installation would not cover its costs for a single use. Hence, there will be no clear peak shaving as visualized in figure 3. Unfortunately the time sorting of R eliminates the possibility to solve this case more accurately. Still, the solutions can be considered to be the minimum storage provided. Also, fair results are achieved if the volatility along the considered time period is small.

3 Discussion

Along the modeling process it is necessary and useful to make some assumptions and to simplify. It is thus interesting to evaluate if the solutions for storage deployment are rather under- or overestimated. Firstly, the linear approximation of the residual load duration curve R makes storage less profitable. The linear function neglects load peak outliers that offer a great arbitrage potential. More realistic characteristics of R may be found in Steffen and Weber (2013). Further electricity demand is not fully time inelastic (Kirschen, 2003). If considering some price elasticity, storage induced lower peak and higher off peak prices would result in demand changes leading to a re-steepening of R (i.e. an increase of b). Additionally in the case of $p = x^2$ one would expect an increase in the aggregated electricity demand (e.g. represented by an increase in a), when aggregated prices ($\int_0^1 p\ dt$) fall. Therefore storage installation may be considered a strategic complement. Additionally, the residual power production is considered to be fully flexible in our model as no ramp up time or costs are considered. These additional restrictions of conventional electricity production offer a further comparative advantage for the more flexible storages.[6] All the effects lead to an underestimation of storage profitability and thus deployment. Finally, as discussed before, the time sorting has a really significant effect on the solution for the energy capacity κ. As described above κ is really likely to be overestimated or could more accurately be considered a upper bound for the energy capacity.

For further simplification, energy and power capacity costs were considered separately. This might be a good approximation if one of the two accounts for a great share of the total costs. And in fact, the cost for one kWh of storage energy clearly exceeds the installation costs for one kW of power capacity - in some systems even over one to two orders of magnitude (Chen et al., 2009). However, the two are hardly comparable in general as the final costs will depend on load volatility, number of load cycles, lifespan etc., which are not included in the model. Careful case to case consideration will be needed to evaluate whether costs of either sort are dominant.

It was proven that for all cases with $p = x$ an increase in the share of RE will result in a rise in storage capacities. This finding is in line with most literature. E.g. Barton and Infield (2004); Chen et al. (2009); Nyamdash and Denny (2013); Steffen and Weber (2013) all emphasize the importance of electricity storage for a transition to a CO_2-neutral power supply. However, the results for quadratically rising marginal production costs ($p = x^2$) show that there might exist opposing effects and the influence of RE installation on storage is not that clear. Empirical data may be used to quantify the derived effects.

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[6] Of course, also storages are restricted by a number of technical characteristics, which will influence their performance and are not (yet) implicated in the model.

In the developed model storage usage must result in lower aggregated electricity costs due to the peak shaving of the supply and the pricing rule ($p = x^2$). However, for $p = x$ aggregated costs are the same even in the monopolistic market as storage has to compete with regular production. Also it is intuitive that aggregated costs may rise if storage losses are considered. The case of rising consumer prices after storage installation is emphasized by Nyamdash and Denny (2013). Also, in the real world a great number of institutional arrangements like price setting mechanisms or subsidies play a significant role for the final ratio of storage and power plants.

As expected the monopolistic market leads to a significantly lower storage deployment compared to perfect competition. Additionally considering storage costs as well as a quadratic cost function of the power plant park ($p = x^2$) should not basically alter that finding. It follows that market power of the storage operators will increase aggregated electricity costs when $p = x^2$.

In a further analysis it would be desirable to extend the model with more technical restrictions like storage losses, which could be done by relaxing equation 5 such as the storage needs to charge more energy as it is able to discharge. Also uncertainty is so far neglected but will probably strongly affect the storage. Further, focus may be set on the institutional framework like the market structure. By integrating multiple agents interacting on an imperfect market it would for example be possible to get intermediate results between perfect competition and monopoly. Moreover, a more realistic model may be developed by the introduction of a space dimension. By modeling the relationship of storage as well as transmission installation decisions one can draw interesting conclusions on optimal strategies to efficiently reach the political provisions for RE.

4 Conclusion

The significance of electricity storage for high shares of RE power production is unquestioned. With the developed model we were able to analyze the market outcome of efficient storage deployment and to draw conclusions on the relationship between the development of storage and RE.

It was shown, that market power reduces storage deployment, thereby generating profits for the operators. Furthermore, considering power costs exclusively, the capacity is fully utilized as long as prices diverge from the competitive price equilibrium and otherwise reduced accordingly. On the other hand, energy capacity costs result in a price differential within operation is non-paying and therefore halted. As soon as the differential surpasses a certain threshold, peak shaving with constant (non-storage) supply plateaus occurs.

Increases in the share of RE induces a steepening of the residual load duration curve that leads to a greater arbitrage potential and thereby more storage deployment under most circumstances. When considering quadratically rising marginal cost of residual load production, the decrease of the peak load following a rise in RE results in a lower amount of storage. Yet, for linearly rising marginal costs the peak load change does not affect efficient storage deployment. The magnitude of the effects may be analyzed using empirical data.

The simplicity of the model allows for an eclectic enhancement and a comprehensive foundation for further research. In next steps the model may for example be extended by uncertainty, storage performance losses, institutional framework or the need for electricity transmission, giving additionally rise to spacial decisions. Thereby research questions of great interest concerning the development of storages and the transition to RE may be conveniently addressed.

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Auctioning of emerging natural monopolies for offshore grid connections

Julien Minnemann[*]

Abstract

Grid connections are the bottle neck of the offshore wind industry. Several problems arise through the legitimate natural monopoly of the transmission network operator. This paper charges the missing incentives for a network operator to work cost efficient under the current situation. As a solution, an auction for construction and operation rights of emerging offshore grids is proposed which differs from the classical franchise auction. I found that the proposed auction mechanism is characterized through standardization process, number of participants and bidding costs as crucial influencing factors. Beside cost efficiency, further advantages as using high quality inputs and a higher construction pace arise with the proposed auction procedure. In addition, regulatory efforts are reduced and asymmetric information between network operator and regulator removed through the construction and operation auction.

Keywords: wind energy, network expansion, incentives for cost efficiency, construction and operation bidding, institutional market design

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[*] Email-address: julien.minnemann@uni-oldenburg.de; Carl von Ossietzky University Oldenburg, Germany

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1 Introduction

The production of electricity through offshore wind turbines is a crucial point of the German Energy Transition. The government announced a goal of 15 Gigawatt offshore wind capacities by the year 2030 (CDU et al., 2013: 39). At the end of 2014, 258 wind turbines with a capacity of 1,049.2 Megawatt produce electricity in the North and Baltic Sea. At the same time 285 wind turbines with a capacity of 1,303.1 Megawatt could not feed in (Lüers and Wallasch, 2014: 3). The main problem the offshore industry is confronted with is the missing grid connection due to a bundle of serious problems of the transmission net operator that is under law responsible for the grid connection. This paper proposes a different allocation procedure. Instead of the right of transmission network operators to construct and operate grid connections, the idea of an auction is presented giving the lowest bidder the right to construct and operate a grid connection. This change in the allocation procedure should deliver a grid expansion being cost efficient and increase the construction rate.

As the transmission network operator is under law the only allowed to connecting offshore wind parks with the grid, there are low incentives to be cost efficient. The result is a slow grid expansion at high cost. A limitation of liability allows the network operator to shift its liability to general public. Politicians start discussing the main problems of this situation and ask for state to take an active part in the offshore grid connection. This paper delivers another approach with a competitive solution.

The grid connection between offshore wind park and onshore grid can be seen as a natural monopoly as it does not make sense to build more than one connection. As Chadwick (1859) already pointed out one solution can be a “competition for the field” if a “competition on the field” is not possible. Demsetz (1968) picked up this idea and argues that a different institutional arrangement like an auction could deliver better results as regulation of natural monopolies. The theory is known as “franchise bidding” which in detail describes an auction in which the company with the lowest cost per unit is allowed to operate a natural monopoly. In contrast to the classical Demsetz theory, the proposed auction should not primarily replace regulation but should deliver a procedure to allocate emerging natural monopolies.

This paper draws on the main idea of a Demsetz-Auction but uses it in a different context. The German Energy Transition delivers a rare situation of emerging natural monopolies. Instead of franchise bidding, the paper proposes a “construction & operation bidding” giving the winner of the auction the right to construct and to operate the grid connection and become a natural monopolist.

To examine the results of the new allocation procedure, the theory of the auction is described in detail. Core elements of this auction are consortia as participants of the auction, the auctioning regulator and the procedure of auction itself. All of the three points are analyzed regarding critical conditions and possibility of success of such an auction.

Within this paper I show the need for a change in the allocation procedure away from only one transmission network operator to a competitive solution. The proposed auction delivers a situation where the incentive is high to work cost efficient and finish projects in time. Instead of the classical franchise bidding, the proposed procedure gives no incentive to deliver bad quality. Even if a regulation agency is still needed, the overall effort of this agency diminishes. Many advantages as an arising standardization process and a relief of the network operator are expected.

The paper starts with an overview of different techniques of offshore grid connections and the main problems within this field. The subsequent chapter presents the “construction & operation bidding” as a different allocation procedure. The advantages of such an auction procedure are given afterwards. The conclusion discusses limitations of this approach and sums up the main results.

2 Offshore grid connection

In Germany paragraph 17d of the EnWG (law on the energy industry) define that the responsible grid operator on land must also take care of the offshore grid connection. For the Northern Sea the operator is TenneT and for the Baltic Sea it is 50Hertz. A grid connection is characterized by the connection of the wind parks with the grid onshore. Within the grid connection, two different methods are distinguished. The first method is used for wind parks close to the coast. A direct three-phase alternating current connection (AC) combines the wind park and the onshore grid directly. However, most of

German wind parks are constructed far away from the coast and have high nominal power. Therefore, high voltage direct current grid connections (DC) are used as this technology has lower transmission losses and can transport a higher power.

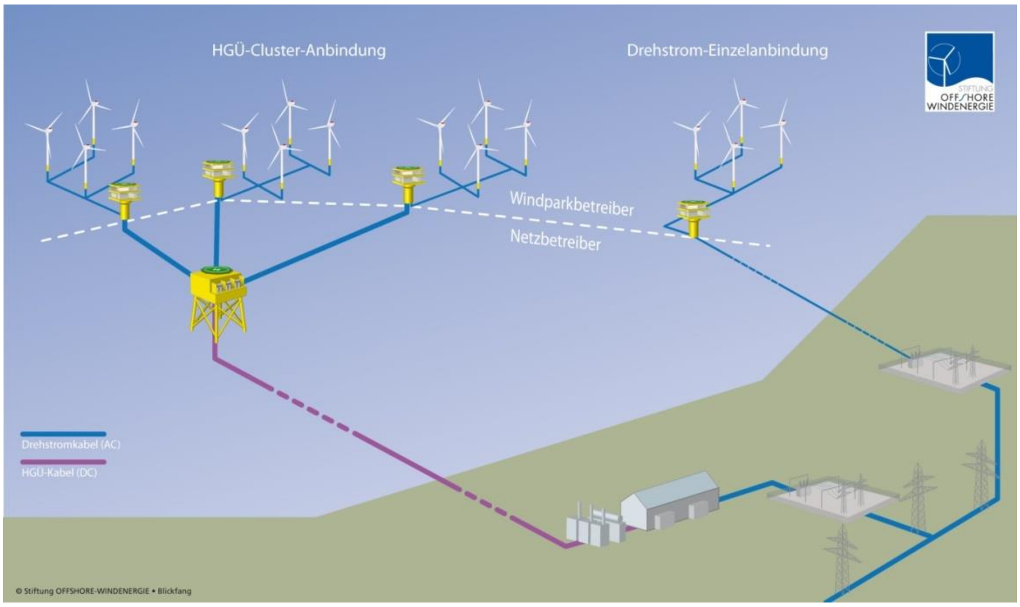

Figure 1: Connection of offshore wind parks (Source: Stiftung Offshore Windenergie)

As it can be seen in figure 1, each wind park has its own transformer station transforming the produced electricity to a higher voltage. In the alternating current connection (AC) the power is transmitted directly to the next transformer station. The prevailing method is the direct current connection (DC) as several wind parks can feed in into one grid connection but especially in the Baltic Sea the alternating current connection is used. Each wind park uses its own transformer station, which is connected to a converter platform transforming the power into direct current. The sea cable transports the power to the next transformer station onshore. The network operator is responsible for the connection of each transformer station to the converter station, its construction and connection of sea cable and next transformer station onshore. In the following that process is referred to as “offshore grid connection”. The set up resembles a natural monopoly by definition as just one connection is efficient. Overall, up to 34 DC and AC connections are needed until 2034 (Feix and Hörchens, 2014: 49-50). Independent which method is used, the result is a natural monopoly of the network operator.

Especially the grid connection turns out to be a bottle neck. Already the first offshore wind parks could not feed in due to a lack of the grid connection. In such cases the wind park operator gets compensations. The network operator is liable for 17.5 million euro per instance in the case of acting carelessly (§17f Abs. 2 EnWG). The evidence of a gross carelessness and therefore a complete liability of the network operator seems difficult as a result of high unforeseeable risks. As offshore wind parks feed in high amounts of power, the sum of liability is depleted fast. Afterwards the compensation is paid through an apportionment of cost to grid charges. In the year 2014, each consumer had to pay 0.25 Cent/kWh for this apportionment. Until the end of 2015, the sum of this apportionment could reach 2.7 billion euro (Pieprzyk, 2012: 2).

Such an apportionment sets wrong incentives for the network operator as most of the liability is generalized and taken liabilities flow back to the operator as a result from the grid fees. Hence, the incentive to complete a grid connection within time and cost budget is low existent. The network operator faces no competition as a natural monopolist. The only possibility to sentence delayed grid connections is in the power of the regulation authority. Proving a careless or even gross careless behavior of the network operator is difficult as there are several risks, some of them outside the area of influence of the network operator as weather conditions or delays of suppliers as well as the existence of asymmetric information (Feix and Hörchens, 2014: 53). As a result of missing incentives to work efficiently it is questionable whether it is possible to introduce competition within the construction of offshore grid connection.

It has to be answered if it is possible to change the current situation or if there are reasons defending the right of the network operator to construct and operate the grid connection exclusively. In theory, there are three reasons why a natural monopoly arises and persists. The first argument is sub additivity, meaning one company can serve the market at lower cost than two or more companies. In the case of offshore grid connections the argument of sub additivity is very important. It can determine that independently of the allocation process a natural monopoly would arise at the end and therefore it is not important who acts as natural monopolist.

The second argument is sunk costs. The argument indicates that market entry is prevented when the new entrant has to invest a lot of money before entering the market. If the market entry is unsuccessful, the costs are lost. As the risk of losing money is high, market entry is prevented.

Finally, the specific knowledge of the existing net operator is another challenge for all possible entrances. But the specific knowledge is not an argument in favor of the net operator per se. In most cases, the network operator acts as a principal assigning the operations to different suppliers. One could argue that the suppliers have specific knowledge in their field of activity. A consortium of these suppliers is able to provide the same work using their acquired knowledge now directly and no longer as a subcontractor. Overall it is possible to change the current situation because neither of the above mentioned arguments prevents an allocation of grid connections to other companies.

As there are just few net operators serving the market, they have strong monopoly power. To control the monopoly power the state regulates the monopoly or operates the monopoly on its own (Ströbele et al., 2012: 291). The used regulation method is incentive regulation for all four network operators. The objective of incentive based regulation is to establish an incentive compatible set of cost comparisons that can be used to determine an efficient firm's revenue needs. Setting revenue caps, all network operators should orientate on the most cost efficient one what is called benchmarking or yardstick competition (Parker et al., 2006: 117). Revenue caps deliver cost efficient results under given quantity and quality. Inefficiencies can arise if either quantity or quality is not given. As there are just two network operators constructing offshore grid connections in North and Baltic Sea a comparison between both is difficult as the requirements are different. Therefrom, the costs of construction are just handed over one-to-one to the grid fees and revenue caps are not a beneficial regulation scheme.

The described problems in the area of responsibility of the net operator are intensified through a lack of suitable regulation fitting the challenges of emerging natural monopolies in the offshore grid connection. Within the next chapter an allocation process is proposed to remove wrong incentives and to reduce regulation to a minimum.

3 Auctioning of natural monopolies for offshore grid connections

Different allocation procedures are possible in praxis. In this paper the focus is set on an auction of each grid connection. The idea goes back to Demsetz (1968) and Chadwick (1859) arguing for competition for the market if competition on the market is not possible. The proposed market mechanism is the auction. With such a mechanism, competition can be introduced even if there is only one company on the market at the end (Hoven, 1992: 33). In contrast to the classical Demsetz-Auction in which the lowest bidder is allowed to serve an existing market, the introduced auction contracts constructing and operating of one grid connection. Therefore it is an auction for a new market. Quality uncertainties are a classical critical matter on Demsetz-Auctions. Quality is an important variable but under the proposed auction it is in the decision of the bidder which quality is offered. With a “construction & operation bidding” there is no incentive to use low quality materials or operate the grid on a low effort level as disruptions would harm the operator directly. As a result, technological efficiency is assured. Given that quality is not a direct part of the auction the only decision variable is the price. Demsetz argues in his paper that an auction would replace regulation. Goldberg (1976) and Williamson (1976) did not follow this argument but see similarities between a Demsetz-Auction and regulation.

The proposed auction offers the right to construct and operate a single offshore grid connection. The auction’s core is the price bid each potential buyer is handing in. The price bid is the amount of money, which a potential buyer charges to transmit a fixed amount of electric energy from the wind parks to the land grid. The lowest bid and so the lowest cost for transmission is winning the auction. The suggested auction delivers a situation where an entrant could lose some money if the auction is not won. Costs can arise due to the bid and forming of a consortium. But these costs are not necessary sunk. As there is a bundle of grid connections being part of auctions, preliminary work can be used for later auctions. As a result the sunk costs are decreasing and are not a barrier to market entry. The auction has three core elements which are analyzed in the following.

3.1 Auction authority

The auction authority is responsible for the implementation of such an auction and has to undertake several design steps before the first auction. Therefore it centralizes all relevant information of all involved actors. With a detailed information base, the auctioning authority announces deadlines for incoming bids adjusted to completion dates of wind parks. The announcement happens several years in advance to allow for a simultaneous finalization of wind parks and grid connection. Furthermore, the announcement should be international and public under the rules of the European Union procurement guidelines, reaching many potential participants. Bidding documents are handed out in which the authority gives information on the auction procedure and sets specifications how the grid connection has to be build. These specifications are a result of requirements of the wind park operator on the one hand and the network operator of the onshore grid on the other hand. With such specifications each potential participant is able to calculate the cost and bid for the grid connection. The contract period should equal economical endurance of the wind parks and grid connection.

In the following, the auctioning authority supervises the process. The lowest bid is identified and the winning bidder is informed. In general, the auction authority should have the right to postpone an auction if the market conditions do not allow adequate results. Furthermore, the authority should be allowed to set a ceiling price adjusted to the regulation price under the old regime. With a ceiling price the authority could ensure price bids smaller than previous regulation prices.

In Germany, especially the Federal Network Agency has practical experiences with implementation of auctions. In the year 2000 and 2010 first experiences with the auctioning of Universal Mobile Telecommunications Systems (UMTS) could be gained. The next UMTS auction is already planned for the second quarter of 2015 (Bundesnetzagentur, 2015). Although these auctions are highest bidder auctions, there is fundamental knowledge how to execute an open, transparent and non-discriminating procedure. Thus, there is the possibility of auctioning offshore grid connections, as the Federal Network Agency which is also responsible for the regulation of network operators, has significant experiences with auction procedures.

3.2 Auction participants

The second core element of the proposed “construction & operation bidding” is the participation of companies in the auction. The effectivity of the auction depends strongly on the number of participants as the price tends to decrease with increasing participants (Hoven, 1992: 116). Furthermore, the risk of collusion is smaller with a higher number of participants (Hoven, 1992: 129).

With the fact of high investment costs, it is probable that not a single company but a consortium of several companies participates in the auction. One possible consortium could exist of former construction suppliers of the network operator. As they have the knowledge through their work as suppliers, a consortium of them is able to construct a grid connection. Such a consortium could consist of different kind of suppliers. Different types of consortia are also possible. A combination of suppliers with finance investors or a cooperation of suppliers and wind park operators is feasible. Banks, municipal energy suppliers and power suppliers can also be members of a consortium.

If one consortium has been founded each member calculates its costs. To calculate the bid all costs are summed up. Knowing in advance the nominal capacity of the wind parks, an approximation of the transported electricity can be undertaken. With the overall cost and the approximated amount of electricity, the price bid for cost of transporting can be calculated. The bids are the lowest electricity transportation charges as overall costs equal the bid times the approximated amount of electricity flowing through the new grid connection in the future. The calculated costs consist of total amount of construction and operating costs as well as a risk premium for all unknown uncertainties. The height of the risk premium is connected to the risk assessment of each participant. If one consortium tries to maximize its profits and sets the price bid above their calculated costs there is the risk of getting undercut by a competitor. Even when there is just one other competitor there is a high threat of losing the auction. As a result the consortium sets prices equal to their calculated cost. As a consortium is given the right to construct and operate the offshore grid, there is a strong incentive for each member to undercut the own cost calculation as it results in higher profits. The other way around is there no incentive to work inefficient because higher cost would decrease profits. How the future profits are shared under the members of a consortium is a matter of negotiation. One possibility is a distribution concerning the added value.

Infrastructure and pension funds are another group of potential participants. Both are characterized through a long investment horizon with requests of steady returns. Both requirements are fulfilled looking at offshore grid connections. As a winner of the auction, the fund would award contracts to construct the grid connection and later on would choose a provider operating the grid.

The network operators can also participate. Differently to the current situation in which only two network operators are allowed to construct offshore grids, the auction delivers the possibility of participation for all network operators. As they have to bear high investment costs for the onshore grid expansion, the auction delivers them more flexibility. In case of unused financial and human resources a participation in a consortium can be aspired. Otherwise a concentration with all resources on onshore grid expansion can be undertaken.

Many projects in history are undertaken by consortia. In these projects, risk or investment was too high for a single firm. An example is the American oil industry. Oilfield owners and refineries shared their cost and ownership on pipelines (Klein et al., 1978: 311). Another example is the joint operation of pipelines connecting refineries on the one hand and airports and airlines on the other hand. These two examples show the possibility of putting projects with high investment sums into practice.

3.3 Auction procedure

The third important point is the auction procedure. As described above, the lowest price bid will be accepted. For this reason a reverse auction is used. As the construction and operation is in the responsibility of the winner, the auction result only depends on the price. For an efficient auction procedure some preconditions have to be fulfilled: (1) There must be a sufficient number of participants in this auction. (2) The right to construct and operate is auctioned and is given to the bidder with the lowest price bid. (3) There is a free access to all needed inputs supplied at competitive prices. (4) Collusion is forbidden. Are these preconditions fulfilled an auction leads to second-best solution compared to free competition (Brautigam, 1989: 1302).

Very important characteristics of the "construction and operation auction" are sealed bids. With sealed bids, only the auctioning authority gets informed about the bids and not the competitors. Keeping the bids secret prohibits strategic interactions within next auction. In case of knowing their competitors' bids the participants start to interact strategical. A situation could arise where a participant does not set price equal to its costs but just under the bid of the competitor. If this bid is higher than the initial decision of price equals costs, a situation arises where the auction does not deliver cost efficient outcomes. Therefore sealed bids are used. In addition, the number of participants each bidder is competing with should be kept secret to avoid strategic behavior of the participants (McAfee and McMillan, 1987: 734).

Using the method of sealed bids delivers a situation where the market entry is theoretically the same for the old network operator and all possible entrants. All have the same chances depending on their price bid only. If one participant has more information compared to the competitors, e.g. regarding some risks, it is the result of his effort undertaken.

The Californian regulation commission used the procedure of a price competition with sealed bids and fixed standards when tendering new electricity generating capacity (Duann et al., 1988: 14). As a result, they found that bidding introduces market discipline and power producers have stronger incentives to control costs (ibid: 59).

With first and second-price auctions, two different auction rules are given in theory. Within this paper it is not distinguished as both rules deliver a situation where the lowest bidder wins. Both price rules fulfill the condition of Pareto efficiency (McAfee and McMillan, 1987: 712).

The outcome of the auction is a contract between a consortium (bidder) and the auctioning authority (bid taker). The bid taker issues the right to construct and operate the grid connection to the bidder under fixed specifications. The bidder committed to construct the grid connection and to operate at the bid price. The operator is responsible for an undisturbed operation and is liable for interferences. If the grid operator is unable to transmit the produced electricity of the wind parks, it has to pay the lost sales to the wind park operators. An indexed contract should be chosen to adapt the price concerning inflation rate or as a function of the change in prices for work-forces, material and resources as well as taxes (Hoven, 1992: 174). This type of contract provides incentives to minimize costs (Joskow, 1985: 63).

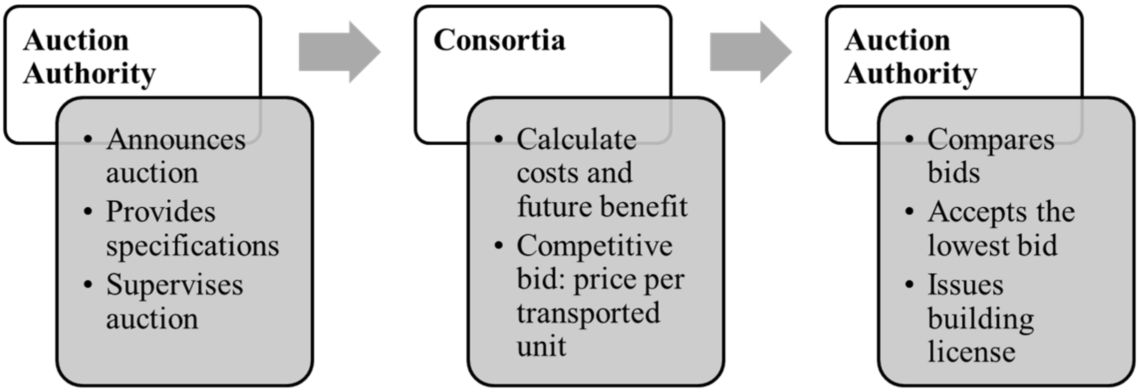

Figure 2: Schematic presentation of the auction mechanism

Costs of bidding are another important influence factor. The auction can be seen as "price search mechanism". In connection with the bidding, costs can arise. Three different kinds of costs can be distinguished. Costs of participation are the first category. Each company has to provide human and financial capacities to be able to participate in an auction. The second category is costs of valuation. A consortium has to undertake potential costs estimations to decide whether to participate in an auction. Overall, these are costs of information and decision making. Costs of bid preparation are the third kind of costs. If the decision to participate in an auction is made, costs for preparation of the bid arise. These costs are connected with the collection of all relevant information to participate (Hoven, 1992: 117). Analyzing construction projects, overall costs of bids can be two percent of the construction sum. But the average value is not expected to be higher than one percent (Finsinger, 1986: 39f.). Construction projects of cable television in the USA under franchise bidding for exclusive supply delivers bid costs of 0.46 percent of overall construction costs (Zupan, 1989: 406).

4 Advantages of a "Construction and Operation Bidding"

A number of advantages arise through an introduction of the proposed auction method. Normally, with the existence of natural monopolies there is high demand for regulation (Windisch, 1987: 56). Beginning with the Federal Network Agency it can be declared that such an auction reduces the demand for regulation as the price is set through the auction and no longer through the agency. With a fixed price the incentive to work efficient is powerful and defective behavior is hitting the company itself. If there is a controversial issue between wind park operator and new network operator, the Federal Network Agency should act as a mediator. In addition, the coordination of all market players is improved. With the Network Agency as centralized planer, the construction of wind parks and grid connections become adjusted.

For the network operators who lose their natural monopoly in the first place, the auction offers more flexibility in the second place. As the Energy Transition demands for huge onshore network expansions, the network operator can concentrate on this work. Furthermore, if they have unused resources they can participate in the auction. In contrast to the previous situation where only two network operators act on the market, all network operator can participate now.

In the relationship between network operator and Federal Network Agency, a typical principal agent relationship is existent. The network agency is the principal and orders the network operator as an agent to act as defined by the agency. But as there is asymmetric information, the information base of the agent is much higher than the one of the principal. The agent starts to maximize its own profit instead of behaving in the favor of the principal (Jensen and Meckling, 1976). Under the old regulatory regime the network agency has to undertake high effort to close the information lag and to regulate the network operator on the base of their available information. With the introduced auction there is no longer the need to gather information concerning the network operator as the price is given through the auction and is not set by the regulator anymore. The used ceiling price is based on prices set by the regulation authority in the past.

The winner of the auction has under these solution high incentives to act cost efficient. As the bid is based on a cost calculation any negative deviation from this calculation decreases future profits. But if there is the chance to undercut the cost calculation, the chance will be taken as this results in higher profits. Furthermore, there is no incentive to use low quality inputs as disruptions would cause missing earnings, high reparation costs and recourse claims of the wind park providers. Careless delays are now in the responsibility of the constructer and no longer handed over to the grid fees.

The liability is not generalized anymore as careless delays during construction are related directly to the new network operator. An allocation to the grid fees is not possible given that the auction price determines the grid fee in advance. An important point is the case of delays which are not in the responsibility of the new network operator due to bad weather. For such cases a cost allocation mechanism must be introduced.

The existence of a small supplier market is one potential risk for the network operator under the old allocation process. A supplier market is characterized through the situation of a small number of potential suppliers and the difficulty to qualify new suppliers due to the complexity of technology (Feix and Hörchens, 2014: 53). But a standardization process is going to be started through the auction procedure as the auction authority summarizes all needed specifications and publishes them before the auction. With predefined specifications more suppliers can be qualified and production costs shrink.

5 Conclusion

The German Energy Transition changes the electricity market radically. Renewable Energies and as an important part offshore wind energy replace fossil power production. The connection of offshore wind parks is one of the major challenges as it proceeds slowly and costly. This paper charges the missing incentives for a network operator to work cost efficient under the current situation. As a solution, an auction for construction and operation rights of emerging offshore grids is proposed. The auction process delivers high incentives for cost efficiency, as the lowest bidder wins. Quality uncertainty does not exist as each new network operator tries to minimize costs and uses components at its best. In addition, regulatory efforts are reduced through the auction and asymmetric information between network operator and regulator removed.

In contrast to the proposed auction mechanism, it can be argued for more participation of the state through capital increases with network operators or an establishment of a new public net operator (Beckers et al., 2014: 299). Further research should be undertaken to analyze the theory of a public net operator and if such one has the same incentives to work efficient as the presented auction mechanism.

The auction especially depends on the number of participants as the lowest bid tends to fall with an increasing number of participants (Hoven, 1992: 129). With a standardization process and clear guidelines, more companies can be qualified and take part in the auction. The “hungry-firm phenomena” where the bidder sets an extreme low price bid and tries to renegotiate the contract afterwards must be avoided. An index-linked contract is the outcome of the auction whereas the price is adjusted to inflation or price changes of components. With an index-linked contract the “hungry-firm phenomena” is avoided through strict price changing parameters. Without evidence for rising cost the by contract agreed price is not changed.

Within this paper it is not argued that regulation is not needed any longer but a reduction in its necessity to intervene into markets is detected. The idea of the Demsetz-Auction is not used as a substitute for regulation. Rather it is used as cost efficient procedure of the allocation of emerging natural monopolies and to introduce a powerful regulation.

Less is known about what happens after lifespan of an offshore wind park. Repowering as well as deconstruction is feasible. The auctioned grid fees are linked to the durability of the wind parks. If the wind park is still at work after the end of the contract duration, the grid fees will be the result of negotiation between the operators of the wind park and the grid connection. Both parties have a strong incentive to reach an agreement due to the mutual dependence of each other. Without an agreement, neither the wind park operator nor the operator of the grid connection takes advantage of such a situation as both would lose money. Therefore, an agreement is probable. If a new wind park is constructed and a new grid connection is needed, it will be the matter of a new auction.

Another crucial point is the bidding costs. If these costs are high, less participation can be expected. Additional research should be undertaken to estimate the costs of bidding in advance. In general, a trial run before introducing an auction should be performed by the Federal Network Agency. It can deliver beneficial experiences.

The difference between first and second price bidding is not pointed out in detail as both delivers a situation in which the lowest bidder wins. Nevertheless, there are important differences especially concerning to the incentive of each consortium to reveal real costs calculation instead of strategic bidding. A deeper analysis should clarify which alternative to choose.

This paper delivers a contribution to the current discussion on how to improve the offshore grid connection. Even if the proposed auction procedure is not realized, a change towards more competition is needed. A first step might be the removal of the restriction that only one network operator is allowed to connect offshore wind parks.

Even the threat of possible market entry forces the incumbent to work efficient (Baumol, 1982: 14). To draw a conclusion, the proposed auction procedure should be introduced as an additional instrument of the Federal Network Agency in the first step. Afterwards the behavior of the network operators has to be observed. If there is no change the Federal Network Agency should use a competitive framework as the “construction and operation auction” as a second step. Under the business as usual regime, the regulation remains toothless and grid connections costly. With an ongoing shift of costs at the expense of end users the public support of the Energy Transition is going to diminish.

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