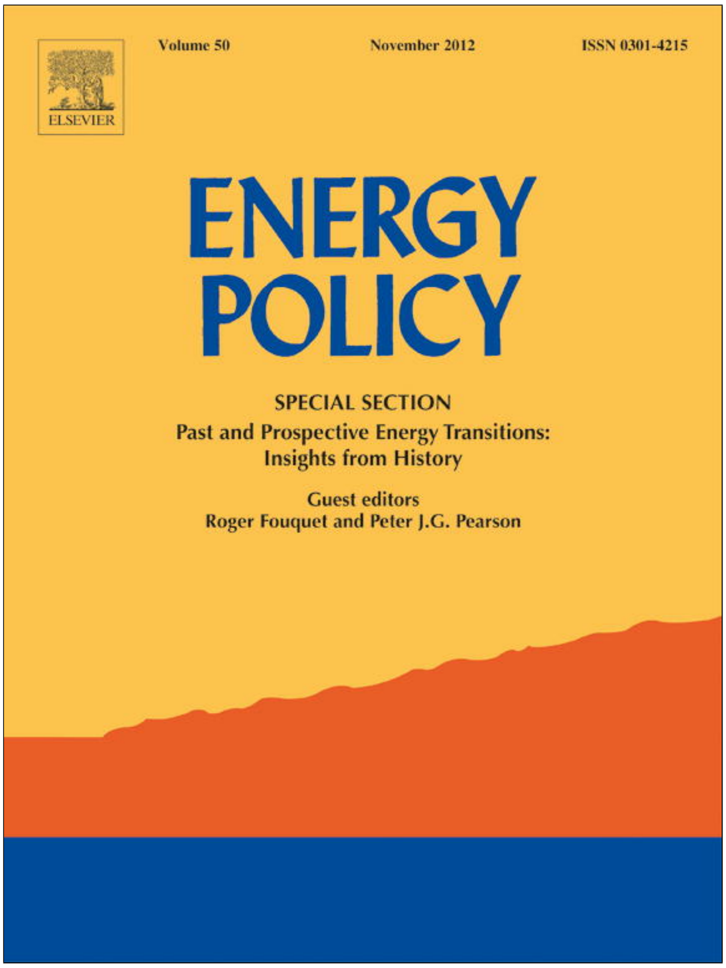
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The role of smart metering and decentralized electricity storage for smart grids: The importance of positive externalities

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HIGHLIGHTS

- Smart meters and decentralized storages are important components of smart grids.
- Both components are widely seen as beneficial to society.
- Identification of the most important stakeholders and their investment incentives.
- Omission of societal desirable actions due to positive externalities.
- Measures to foster diffusion of smart grid key components.

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ABSTRACT

Because of its fluctuating nature, the feed-in of renewable energy sources into low-voltage distribution grids complicates the balancing of demand and supply. This carries the risk of grid instabilities causing damage to electronic devices and power outages, which eventually lead to deadweight losses. In principle, the problems arising from fluctuating feed-in can be solved by increasing demand elasticity or decoupling generation and consumption; for the first, an advanced metering infrastructure and, for the second, decentralized electricity storage are considered core enablers. However, to date, the diffusion of these future smart grids' core components is low. The present study provides new insights for understanding and overcoming diffusion barriers. For this purpose, a qualitative research approach was chosen. The most important stakeholders as well as related private costs and benefits are identified. The findings show that both of these smart grid components are widely considered beneficial to society by experts. However, because the numerous private benefits are widely distributed among distinct players, socially desired investments are hampered by positive externalities. The importance of well-designed and consistent regulatory and legal frameworks that provide economic incentives to involved stakeholders is highlighted in the results.

1. Introduction

Energy markets are changing rapidly and will lead to a substantial transformation of electricity systems. Conventional energies (e.g., coal, nuclear) will increasingly be substituted by fluctuating renewable energy sources (RES) (e.g., wind, solar). A lot of this energy will be fed into the low-voltage electricity grid. As periodically volatile consumption meets weather-dependent production, the exact balancing of demand and supply already is and will become a complex challenge (Mattern et al., 2010). This is one of the most critical issues in the transition to less carbon-emitting energy supply systems within the next decades (Christian, 2010). This study focuses on Germany, since the expansion of intermittent RES is particularly high there (Nitsch, 2008). However, the results can be applied to other countries seeking to increase renewable energy usage.

The German reaction to the Fukushima accident is accelerating such expansion. After a three-month moratorium, Germany decided to permanently shut down 8 nuclear power plants immediately and the remaining 9 before 2022 (Economist, 2011; Nestle, 2012), which dramatically reduces base load generation. Thus, studying the German electricity market is particularly interesting if the impact of an increasing RES penetration is to be understood. Owing to generous financial support by means of a stable feed-in tariff since 2000, electricity generation from renewable sources has increased dramatically. In 2011, the RES share of net electricity

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consumption in Germany was 20.0%, equaling 121.8 TWh in absolute terms (AGEB, 2012). Due to skyrocketing photovoltaic installations in the last decade, the so-called “reallocation charge” for the promotion of renewable energies increased ninefold. On average, consumers are charged 23.42 ct/kW h in 2012, of which 3592 ct/kW h is a reallocation charge, with the result that electricity prices in Germany are among the highest in Europe (BNetzA, 2012; Eurostat, 2010). Because intermittent wind and photovoltaic account for most of the installed capacity of RES (82.3%), the feed-in of RES fluctuates significantly. Since network providers must, by law, give preference to power generated by renewables, conventional power plants have to adjust their production on an increasingly regular and unpredictable basis. The result is that, because of the “merit-order effect” (Sensfuß et al., 2008), existing conventional power plants’ profitability decrease, and the calculation of returns on investments in new power plants’ construction is associated with great economic uncertainty. Therefore, the high penetration of intermittent RES and the current market design are already severely straining the stability of the German energy supply system.

To address the fluctuating feed-in of RES, two general approaches exist: increasing demand elasticity or store surplus power. To match fluctuating electricity generation and demand and “to ensure economically efficient, sustainable power system with low losses and high levels of quality, security of supply and safety” (ERGEG, 2010, p.18–19), the smart grid concept emerged. Globally, policy-makers, practitioners and researchers focus intensively on smart grid infrastructures, because the impact of energy systems on society and economy is enormous. While there is still no clear picture of the smart grid architecture, advanced metering infrastructure (AMI) and decentralized electricity storage (DES) are widely considered to be core components (EC, 2006). AMI provides near-to-real-time information on consumption and facilitates demand modulation, which helps improve and optimize the ways in which electricity is generated, distributed and consumed (Kranz, 2011; Kranz and Picot, 2011). Because AMI and smart meters are seen as core components to enable the realization of smart grids’ expected benefits, many countries are investing heavily in their rollout (Faruqui et al., 2010; Haney and Pollitt, 2009; U.S., 2008; Wissner and Growitsch, 2010). The required investments are estimated to be enormous: Faruqui et al. (2010) estimate an investment of €51 billion for the European Union. While from a technical perspective an AMI rollout is considered possible, it is not yet clear to all the involved stakeholders how a smart grid will evolve in practice (EC, 2010). Besides the information-based approach of AMI, electricity storage can buffer excess energy, balance supply and demand, and can thus increase the amount of renewables that can be installed without risking instabilities (Hennessy and Kuntz, 2005). In Germany, the main type of storage presently being used is centrally installed pumped hydro. Combined, it provides power of 7 MW and a capacity of 0.04 TW h (SRU, 2010). Because the potential of expanding pumped hydro in Germany is seen as very small, it is necessary to foster the diffusion of other storage technologies as batteries, which can be implemented in a decentralized way. The most promising technology in this field is the lithium-ion battery. However, today it is still too expensive for many applications and further development to decrease costs (currently 500–1000€/kW h) is crucial (Wietschel et al., 2010). In order to fully move to RES, it is estimated that Germany needs to increase its storage capacity dramatically (Economist, 2011). As in the case of AMI, even though technically possible, it is not yet clear how the diffusion of DES will develop, who the most important actors are and what roles they will play in a solution.

Hammons (2008) presents different possible system architectures for the integration of renewables into European electricity grids. In these, DES and AMI play an important role. According to Ipakchi and Albuyeh (2009), especially in the distribution grid, the two components are crucial technologies. Thus, this study focuses on how the diffusion of these two smart grids’ key enablers can be fostered and how renewables can be integrated more effectively.

This explorative research makes the following contributions: first, the authors identify stakeholders and discuss their opportunities and risks. New insights on smart meters’ and DES’s low diffusion are provided. Results are derived from qualitative interviews with industry experts and provide an understanding of their assessments and strategies. Hence, whether there are situations of positive externalities in smart grids’ emergence is explored. Second, the authors analyze whether new incentives and regulatory intervention are necessary, identifying measures to foster diffusion. Important questions for further research are then identified.

The remainder of this study is organized as follows: In Section 2, related literature is reviewed. Section 3 provides an overview of the theoretical concept of externalities. In Section 4, the applied methodology is explained. Section 5 presents the qualitative study, the sample, the data collection and the data analysis. The findings and results are presented in Section 6, while Section 7 provides a conclusion and discusses managerial and political implications. The study limitations are discussed and avenues for further research are outlined in Section 8.

2. Related literature

2.1. Decentralized electricity storage

Given that the construction of large-scale pump storage is geographically confined, new approaches to store electricity are necessary (Wietschel et al., 2010). The function of electricity storage is to temporally decouple generation and consumption. A wide range of technologies exist for electricity storage and diverse applications. An overview follows:

Storing electricity can either be accomplished directly by storing electrical energy (e.g., in capacitors) or indirectly by conversion into mechanical-potential energy (e.g., pumped hydro storage, compressed air), mechanical-kinetic energy (e.g., flywheels) or electrochemical energy (e.g., lead acid battery, lithium-ion accumulator, redox-flow batteries, hydrogen storage). When stored indirectly, the energy must be reconverted into electricity prior to utilization. In literature, the term energy storage is sometimes also used for load management (e.g., demand side management), which is then called virtual energy storage. As this can be enabled through AMI, when exploring storage, this study focuses on physical storage as a component of a smart grid. Fig. 1 provides an overview of different electricity storage technologies.

Energy storage types can also be distinguished in relation to their application and related power. There are four storage types: central storage power plants[1] are connected to the high-voltage grid, massive decentralized battery storage systems[2] are connected to the high-voltage and medium-voltage grid, local small storage is connected to the low-voltage grid, and short-time storage[3], which is used to increase power quality. Even though a high need for increased electricity storage capacity is anticipated, it is not clear whether most of required storage will consist

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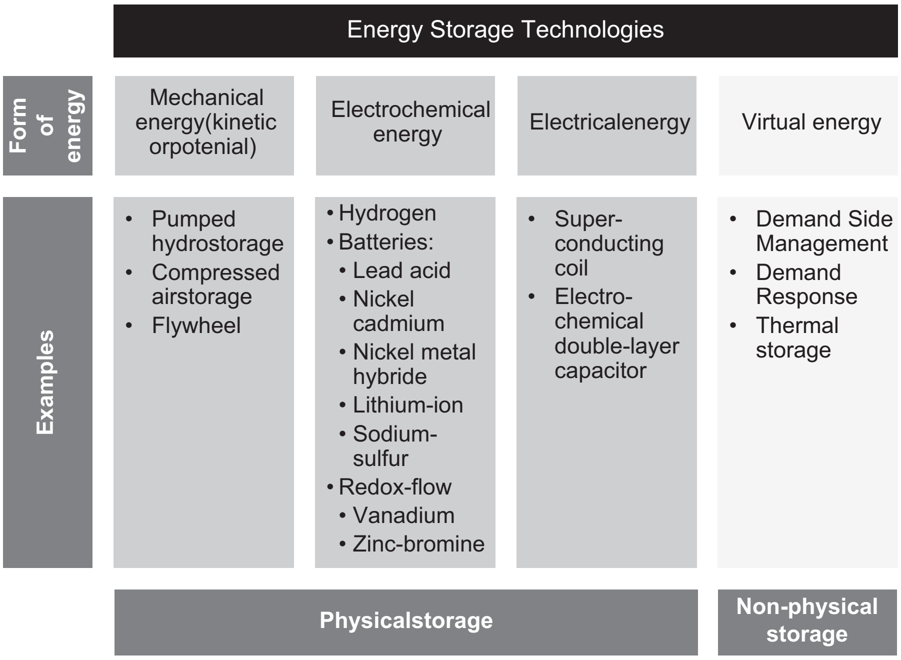
[1] Centralized storage power plants have power outputs over 100 MW. The usually applied technology is pumped hydro. In rare cases, other technologies such as compressed air or hydrogen are also used.

[2] Decentralized huge battery systems have power outputs of 1 to 100 MW. The usually applied technologies are lead acid, nickel cadmium, sodium-sulfur and redox-flow.

[3] Short-time storage can have a wide range of power outputs in the magnitude of W to MW, but all have small capacities (kW h). The usually applied technologies are flywheels and double-layer capacitors.



Energy Storage Technologies				
Form of energy	Mechanical energy(kinetic orpotenial)	Electrochemical energy	Electricalenergy	Virtual energy
Examples	• Pumped hydrostorage • Compressed airstorage • Flywheel	• Hydrogen • Batteries: • Lead acid • Nickel cadmium • Nickel metal hybride • Lithium-ion • Sodium-sulfur • Redox-flow • Vanadium • Zinc-bromine	• Super-conducting coil • Electro-chemical double-layer capacitor	• Demand Side Management • Demand Response • Thermal storage
	Physicalstorage			Non-physical storage

Fig. 1. Energy storage technologies. (based on Wietschel et al., 2010, p.521).

of centralized or decentralized storage systems (Andreyeva et al., 2011). This paper focuses on local small storage, because the authors address issues of low-voltage grids' stability, which is the most critical issue today. Local small storage has power outputs of 1 kW to some 100 kW. Generally, the battery technologies are lead acid, nickel cadmium, nickel metal hybrid and lithium-ion (Wietschel et al., 2010).

To improve the integration of renewables into the low-voltage grid, local small storage systems can either be installed close to prosumers (e.g., combination of a consumer and a producer) (DKE, 2010)[4] or directly at prosumers (e.g., in the basement of households) (Römer and Lerch, 2010).

Previous research has primarily dealt with technical issues of integrating DES systems into electricity grids (Cau and Kaye, 2001; Kakigano et al., 2006), their impact on power system stability (Divya and Østergaard, 2009), arbitrage value of storage devices in specific regions (Sioshansi et al., 2009) or specific applications such as wind farm repowering projects or island systems (Hennessy and Kuntz, 2005). Furthermore, there is research on specific incentive methods for DES systems, such as the compensation for self-consumption of electricity produced by photovoltaic systems, which show that technologies for DES are still too expensive for most use cases (Römer and Lerch, 2010).

2.2. Advanced metering infrastructure

AMI includes a smart meter (comprised of an electronic meter and a communication gateway) combined with an advanced metering management system and metering infrastructure (ERGEG, 2007; Haney and Pollitt, 2009; NETL, 2008). The following three tasks can therefore be achieved: real-time usage data measurement and recording; giving customers the possibility to participate in demand response programs; and the supply of data to monitor voltage and facilitate other service issues (Kranz, 2011).

Smart meters are central gateways located on the customer's site that support two-way communication. Thus, AMI bridges the communication gap between consumers and other energy systems' parties by means of information and communication technologies (Kranz, 2011). The new metering infrastructure is essential for energy efficiency measures, the monitoring and management of grids as well as load balancing and shifting, for example (ERGEG, 2007). AMI thus increases information exchange transparency among all involved players and allows more efficient and anticipatory coordination between power generation and power consumption (Yang et al., 2009). In comparison to regular meters, smart meters are also able to show detailed consumption information in near-real-time and allow for direct feedback so that demand can be adjusted. Previous research has primarily dealt with technological issues concerning smart meters (Darby, 2008). However, recent research has dealt with consumer-related issues. Some studies, for example, analyzed consumer acceptance of AMI (e.g., Kranz, 2011). Other research has focused on the consumer and utility benefits of AMI (e.g., NETL, 2008) or focused on solutions that are enhanced by information systems such as green information systems to address environmental sustainability (e.g., Melville, 2010; Pupillo et al., 2009; Watson et al., 2010). Furthermore, much research has focused on regulatory factors concerning the energy market and smart metering (e.g., Bird et al., 2005; Haney and Pollitt, 2009; Menz and Vachon, 2006; Zhang and Nuttall, 2011). Some research has found that environmental concern is positively related to the adoption of eco-innovations (Jansson, 2009). Yang et al. (2009) note that in an AMI scheme, suppliers, estate managers and consumers are direct contributors. In Germany, since 2010, electric power companies are legally obligated to install smart meters in new buildings (Müller, 2010). Thus, according to Böning et al. (2010), the increasing use of smart meters is more a result of regulation than of industry initiatives. Other research found that replacing standard meters with smart meters leads to an electricity consumption decrease of 3.7% (Schleich et al., 2011) to 15–20% (Gans et al., 2011) or found that smart meters help combat electricity thefts (Depuru et al., 2011).

Even though the diffusion of smart meters is low, several publications estimate the impact of dynamic pricing on peak

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[4] A prosumer can, for example, be a household with a rooftop-installed photovoltaic system.

loads. According to the European Energy Exchange, the delivery times of peak loads are Monday to Friday between 8:00 am and 8:00 pm (Burger et al., 2006). Germany, on which this study focuses, is a winter-peaking nation (Nicolosi and Fürsch, 2009). Faruqui and George (2005) analyzed dynamic pricing's impact on peak loads. They found that time-variable pricing leads to a reduction in peak period energy consumption (the average reduction in this pricing pilot experiment was 13.1%). Stromback et al. (2011) found that peak consumption reductions due to load shifting can be induced to a small extent on a daily basis with time-of-use (TOU) (5% reduction) and real-time pricing (RTP) (12%) and to a bigger extent through critical peak pricing (CPP) (16%) and critical peak rebate (12%); however, the latter two only for critical peak periods. This is in line with other studies that show the influence of dynamic pricing on consumers' daily consumption pattern (Räsänen et al., 1995). For the U.S. market, energy costs are estimated to decrease by $3 billion a year using demand response to reduce peak demand by 5% (Faruqui and Palmer, 2011). Moholkar et al. (2004) found that a load shifting of 30–40% could be achievable through TOU and RTP. Others identified that CPP tariffs lead to a peak demand decrease of 13–20% and, with enabling technologies, up to as much as 27–44% (Faruqui and Sergici, 2010).

3. Theoretical framework

This study focuses on understanding the slow diffusion of DES and smart meters as core component for AMI. As a theoretical framework, the concept of externalities, embedded within the theory of transaction costs and property rights, is used (e.g., Ferguson and Keen, 1996). Property rights theory deals with the design and allocation of an actor's rights to use a good. Transaction cost theory is concerned with costs to transfer property rights from one actor to another (Picot et al., 2008).

This study focuses on positive externalities, a specific form of external effects. In general, there are consumption externalities and production externalities (Varian, 2002). External effects exist whenever one actor's indifference curves depend on consumption (consumption externality) or production (production externality) by another actor (Buchanan and Stubblebine, 1962; Graaff, 1957). The authors of this paper use the term actor to refer to both companies and individuals, and consider consumption externalities and production externalities. Both situations can create problems and may result in non-Pareto-efficient outcomes. Pareto-relevant externalities are usually employed by economists who use the term externality. It is assumed that actors only optimize their own private benefits, without considering the effects of their actions on others (i.e., social costs and benefits), which leads to deadweight losses (Buchanan and Stubblebine, 1962).

Another way to distinguish externalities relates to their effect on other actors, or society (Varian, 2002). Negative externalities are defined in general economic theory as an action of one actor that has negative effects to at least one other actor (e.g., a tanner that pollutes a river with his production and thus reduces the profit of a fisherman downstream). Such situations can result in actions (benefiting one actor) even though they are inefficient on a social scale. In contrast, positive externalities are defined as actions that have positive effects on at least one other actor (e.g., a beekeeper who increases the profits of a nearby orchard because his bees pollinate the fruit) (Picot et al., 2008; Varian, 2002). For the purpose of this study, whenever the authors refer to the term positive externality, they consider only a subsection of positive externalities, which is defined as the sum of social and private benefits exceeding private costs, with less private benefits than private costs, in other words, an economically unattainable situation. Such a situation can lead to the omission of an action (because no actor receives sufficient benefits) that is generally desired by society (see the situation analysis in Fig. 2) (Picot et al., 2008; Varian, 2002).

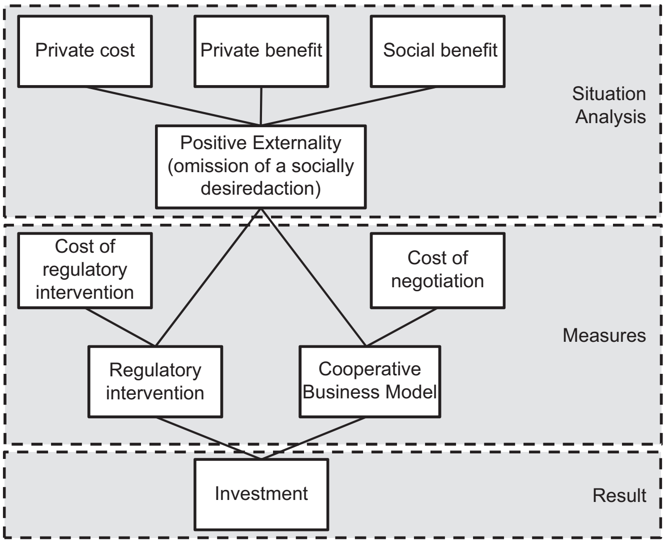


Fig. 2. Illustration of the theoretical framework.

This study focuses on this specific positive externality type. The authors analyze situations in which the benefits for actors might be too small to perform an action, even though the benefits for society as a whole would be huge. To overcome such a situation, the authors see two possible paths: regulatory intervention and cooperation between various actors who derive benefit. However, while both paths have associated costs, they may lead to the socially desired action of investment in smart grid components (see Fig. 2).

4. Method and procedure

To explore fundamental research questions in a new research field such as this study's context, qualitative research is an adequate method as traditional data collection methods are inappropriate, for example owing to a lack of quantitative data (Schlee et al., 2009). Qualitative research is an established research methodology in many social sciences (Rossiter, 2009). Other studies concerning smart grids, particularly smart metering technology, have also used qualitative research approaches (e.g., Darby, 2010). Hence, to answer the research questions, the present study employs a qualitative interview method, conducting and analyzing interviews with field experts.

4.1. Sample

The authors conducted 8 in-depth interviews with German experts in mid-2011. To interview a varied pool of participants, they conducted the interviews with experts from different industrial sectors (Brunk, 2008). They recruited experts by using direct contacts, addressing them on conferences, fairs and via secondary contacts. Regardless of their different individual backgrounds, all interviewed experts have extensive knowledge and several years of experience in the research field. The study sample consists of experts from different hierarchical levels. Table 1 provides an overview of the study participants.

Table 1
Overview of interviewees.

1	Managing director of a venture capital and private equity company
2	Manager of strategy and business development in a large telecommunications company
3	Scientist in a leading position in a policy consultancy in the field of technology assessment and energy markets
4	Chief executive officer of a consultancy specializing in utilities
5	Manager of the development of systems that integrate solar systems and DES
6	Manager of the telecommunications department of a large German public utility
7	Team leader for the development of a DES system
8	Project manager of a large, publicly funded German pilot project

4.2. Data collection

Before interviewing the participants, an email was sent to the interviewees to provide an overview on the interview topic and to give them the opportunity to prepare for the questions. At the beginning of each interview, the authors briefly introduced themselves and explained the research goal before asking the interviewees about their professional position, current work and experience in the field of research.

The interviews sought the experts' views on the value and diffusion of AMI and DES technologies. Interviewees were asked about their evaluation of the economic value of the widespread use of these technologies as well as reasons for the current weak diffusion in Germany. They were also asked which stakeholders they consider most engaged with the two components and what costs and benefits of a wide implementation would occur to them. Furthermore, they were asked about possible incentives to foster implementation of both technologies and how regulatory intervention could look like.

As after 8 interviews, only a few new aspects emerged in the interviews, indicating that the saturation level had been reached (Rossiter, 2009). Thus, the authors conducted 8 interviews with experts, which is in line with McCracken (McCracken, 1988).

4.3. Data analysis

There are different qualitative interview data analysis approaches (see Glaser and Strauss, 1999; Mayring, 2008; Spiggle, 1994). The methodology proposed by Glaser and Strauss aims at theory generation (grounded theory) (Glaser and Strauss, 1999). Spiggle (1994) focused on evaluating interviews with consumers. For the present analysis, the authors used an approach by Mayring (Mayring, 1985, 2008), which is widely used and accepted in literature for similar contexts and analyses (see Binz and Truffer, 2009; Krank and Wallbaum, 2011; Lienert et al., 2006; Niedermeier and Bartsch, 2011; Sigel et al., 2010).

Specifically, the authors used the structured content analysis suggested by Mayring for semi-structured interviews, which seeks to filter certain aspects of the collected material and to evaluate it in terms of certain criteria. Several steps are recommended (Mayring, 2008), which the authors applied on their analysis and will now describe.

The interviews were taped and transcribed verbatim (Lamnek, 1995). As the interviews were conducted in German, they were first transcribed in German. In the further analysis, the results and findings were translated into English using constant contextual comparisons during the analysis (Suh et al., 2009).

The interviews were then paraphrased and shortened. The material was then sorted in two structuring dimensions—the two considered technologies according to the interview guideline. In a following step, the authors derived a category system with clearly defined categories (such as social benefits or private costs) from the theoretical framework and research questions. The authors annotated a typical example to each category and agreed on coding rules to achieve a correct classification of interviewee statements. This is an established categorization procedure. In the next steps, the authors first went through the material coding statements by marking certain passages and then rearranging them according to topic, to facilitate easy comparison and interpretation. During this process, the authors checked coded transcripts for appropriateness and adapted coding rules accordingly. In a following step, all interviewee statements were sent to the participants for validation and confirmation. As a last step, the authors refined and finalized the findings and organized them in tables.

5. Findings on positive externalities

5.1. Situation analysis for the component smart meter

This section addresses general social benefits that arise from the utilization of smart meters as the core component for an AMI. Second, the most important stakeholders as well as private benefits and costs for each of them are presented.

5.1.1. Social benefits of widespread smart meter usage

Our analysis shows that, generally, nationwide smart meter diffusion is considered economically desirable by the majority of interviewed experts.

A widespread use of smart meters is desirable in order to increase transparency and competition in the electricity market. —Manager of strategy and business development for a large telecommunications company.

Our market view is that a mass rollout is economically reasonable. —CEO of a consultancy specializing in utilities.

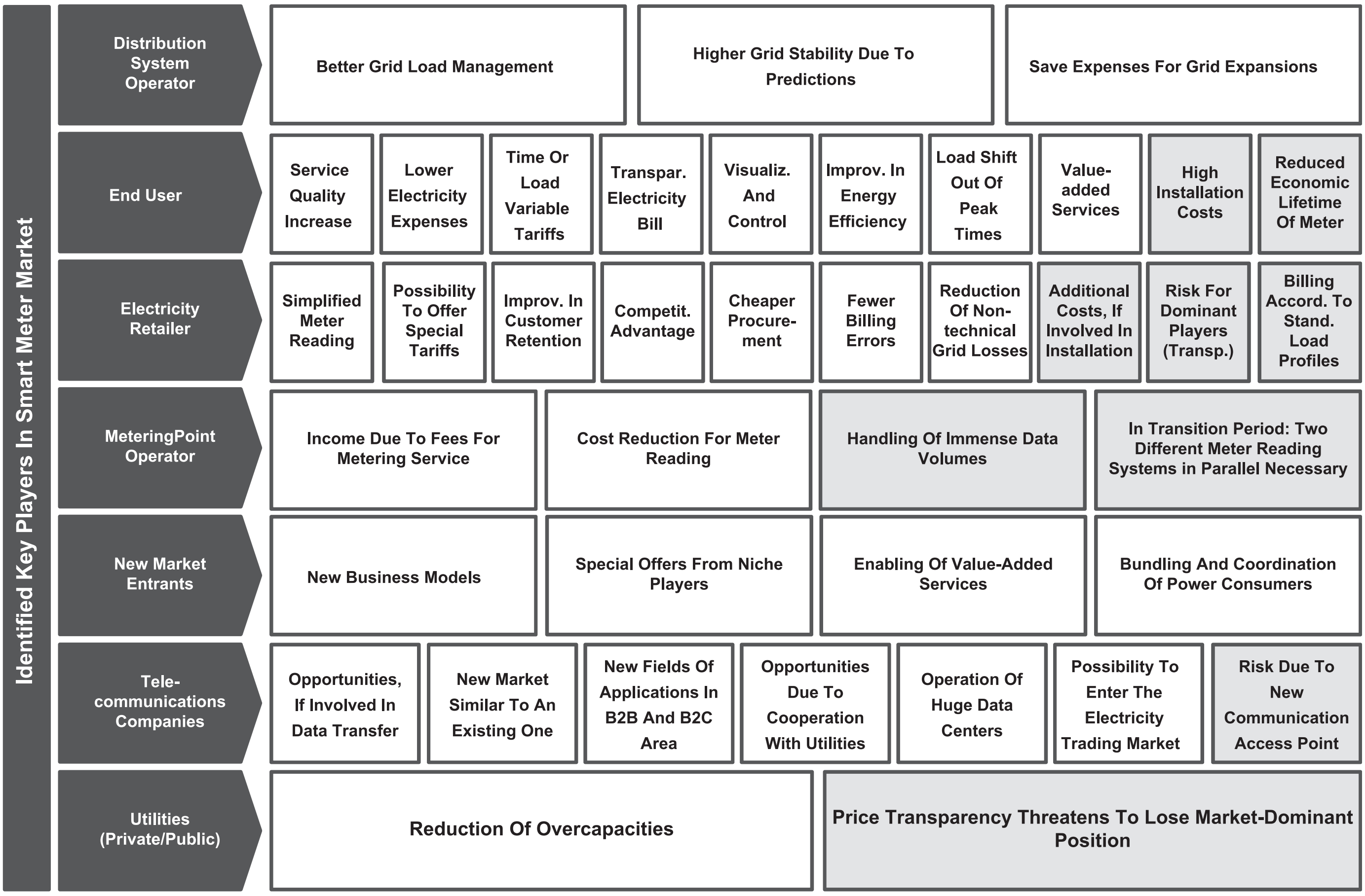
At a macro-level, experts see the opportunity for increased transparency and competition as well as better monitoring and control opportunities to maintain electricity grid stability. Some benefits can only be realized in a mass rollout such as an improvement of balancing and process efficiencies on the utility side. Therefore, most interviewees noted that smart meters should either not be installed at all or should be rolled out on a large scale.

Even though most interviewees were in favor of a rollout, some do not yet have a clear opinion. Before investing, they see the need for an in-depth cost-benefit analysis and for more research on private and commercial end user reactions on variable tariffs.

Although most consider a rollout to be positive, one expert argued against it, reasoning that end user savings are too small and will not outweigh the high costs of an AMI rollout.

5.1.2. Private benefits and costs of smart metering

The most important stakeholders in smart meter implementation, as identified and assessed in the interviews, are distribution system operators, private and commercial end users that could have own electricity production (i.e., prosumers), electricity retailers, metering service providers and metering point operators, telecommunications companies, private and public utilities



Identified Key Players In Smart Meter Market

Distribution System Operator	Better Grid Load Management	Higher Grid Stability Due To Predictions	Save Expenses For Grid Expansions							
End User	Service Quality Increase	Lower Electricity Expenses	Time Or Load Variable Tariffs	Transpar. Electricity Bill	Visualiz. And Control	Improv. In Energy Efficiency	Load Shift Out Of Peak Times	Value-added Services	High Installation Costs	Reduced Economic Lifetime Of Meter
Electricity Retailer	Simplified Meter Reading	Possibility To Offer Special Tariffs	Improv. In Customer Retention	Competit. Advantage	Cheaper Procure-ment	Fewer Billing Errors	Reduction Of Non-technical Grid Losses	Additional Costs, If Involved In Installation	Risk For Dominant Players (Transp.)	Billing Accord. To Stand. Load Profiles
MeteringPoint Operator	Income Due To Fees For Metering Service	Cost Reduction For Meter Reading	Handling Of Immense Data Volumes	In Transition Period: Two Different Meter Reading Systems in Parallel Necessary						
New Market Entrants	New Business Models	Special Offers From Niche Players	Enabling Of Value-Added Services	Bundling And Coordination Of Power Consumers						
Tele-communications Companies	Opportunities, If Involved In Data Transfer	New Market Similar To An Existing One	New Fields Of Applications In B2B And B2C Area	Opportunities Due To Cooperation With Utilities	Operation Of Huge Data Centers	Possibility To Enter The Electricity Trading Market	Risk Due To New Communication Access Point			
Utilities (Private/Public)	Reduction Of Overcapacities	Price Transparency Threatens To Lose Market-Dominant Position								

White boxes: private benefits; grey boxes: private costs

Fig. 3. Key stakeholders in the smart meter market and their private costs and benefits.

as well as new market entrants. In addition to the stakeholders the authors identified many benefits, advantages and opportunities that could be realized due to smart meters, as well as costs, disadvantages and risks for each of the actors. Because smart meters provide measuring data and this information can be used by various players (ERGEG, 2007), relations are manifold and complex.

> *Smart meters are at first just a measuring system. Just having the information itself is not a created value. Not until someone is processing and using the data, thus, creating value, it starts getting interesting*—Team leader for the development of a DES system.

The diverse effects and impacts of smart metering on distinct stakeholders are illustrated in Fig. 3, allocating private costs (displayed as grey boxes below) and benefits (displayed as white boxes below) to the various players. For reasons of clarity, the table does not distinguish between private and commercial end users with or without own electricity generation facility. Furthermore, costs and benefits that were mentioned for smart metering service providers appear in the row for the metering point operator. Other actors that have been mentioned are not included in Fig. 3, because they were not seen as key stakeholders by most interviewees, as the automotive industry (owing to an expected increase in electric vehicle penetration), energy wholesale market traders, energy exchange and traders, responsible organizations for balancing groups, and electronic component manufacturers (e.g., smart meters, plugs, cables, photovoltaic and storage systems).

Smart meters' most important drawback – besides uncertainties, risks and transition problems – is significant investments[5]. These private costs of stakeholders are contrasted by numerous advantages and opportunities, which are widely spread across all players. This clearly indicates a situation of positive externalities: On the one hand, as argued above, smart meters are generally assessed as beneficial for society, reflected in part by the many identified private benefits. On the other hand, the authors see low smart meter diffusion, because high implementation investments are not outweighed by private benefits for any of the single stakeholders, which lead to the omission of an action that is considered beneficial to society.

5.2. *Situation analysis for the component decentralized electricity storage*

This section focuses on DES. First, an overview is given on the general social benefits resulting from an implementation of DES systems. Second, the most important stakeholders and identified private benefits and costs for each of them are presented.

5.2.1. *Social benefits of the widespread use of decentralized electricity storage*

DES implementation is generally seen as having a high value for society. DES are seen as an important factor for the integration of RES, especially of wind and solar energy. Further reasons that

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[5] Investments into smart meters will presumably appear on end users' or electricity retailers' accounts.

were mentioned are the possibility of avoiding energy losses from electricity transmission over long distances[6] and the limitations of pumped hydro. Especially between households and distribution system operators, a win–win situation could evolve. None of the interviewees mentioned that DES is generally economically undesirable, even though one interviewee was indecisive and sees the need for further research to achieve a quantification of costs and benefits. The approach with DES could be compared to a high degree of load management, gas-fired power plants and the approach to supra-regional balance so as to benefit from stochastic effects. Although 7 of the 8 experts argue in favor of DES deployment, on a closer look, the assessments differ significantly. On the one hand, the respondents disagree on the time needed for large-scale DES implementation; the periods range from one year, to more than five years, to as-yet-undefined:

> *Excess electricity is an economic problem. Electricity storage separates the up to now necessary symmetry and simultaneity of consumption and production. From next year on many decentralized storage systems will be brought to market and installed.*—Team leader for the development of a DES system.
>
> *I believe that decentralized storage will come to supplement decentralized generation from renewables. However, the topic is not that far developed as the field of smart metering and I do not think that an economical applicability will be reached earlier than in five to ten years from now.*—CEO of a consultancy specializing in utilities.
>
> *First, it needs to be analyzed if balancing of supply and demand could not be organized in a more efficient way by load management or using regional gas-fired power plants.*—Scientist in a leading position in a policy consultancy in the field of technology assessment and energy markets.

On the other hand, a project manager of a German large-scale pilot project mentioned that DES implementation is generally desirable, but only in regions with particular characteristics.

> *Decentralized electricity storage should be installed at specific points, where it creates especially high benefit, for example if it is possible to avoid grid expansion.*—Project manager of a large, publicly funded German pilot project.

Furthermore, at present, most interviewees regard the DES systems field as underdeveloped. Research is needed, since battery technologies are still too costly and sustainable business models must be developed.

> *With integrated business models and tariff-based incentives decentralized electricity storage turns out to be an interesting concept. I consider it as economically reasonable.*—Manager of the development of systems that integrate solar systems and DES.

5.2.2. *Private benefits and costs of decentralized electricity storage*

The most important stakeholders that were identified concerning DES implementation turned out to be the same players as in the case of AMI. In this case, other identified actors that were less important were players in the reserve energy market, electronic component manufacturers, research and development companies and the energy exchange operator. However, even though identified key stakeholders are the same as above, the identified opportunities, advantages, risks and disadvantages are different. Again, high investments play a significant role, because batteries are very costly in comparison to pumped hydro plants, for example. Owing to high battery costs, DES for prosumers are usually dimensioned too small to provide ‘‘electricity autarchy’’.

> *If you have a 10 kW p photovoltaic system on your roof and then you install for example a 10 kW h lithium-ion storage system—with today's prices this would cost more than 12000 Euro. However, when the sun is shining such a system would be fully charged after only one hour. When charging with full power at ten o'clock in the morning, the battery is full at eleven o'clock. Then produced electricity has to be fed into the grid or the solar system has to be switched off.* —Manager of the development of systems that integrate solar systems and DES.

Other private costs are energy losses owing to low storage efficiencies. Furthermore, for electricity retailers and utilities, DES at end users can lead to considerable disadvantages, because electricity sales might decrease and storage-equipped prosumers could act as competitors to gas-fired power plants.

These private costs of diverse players are contrasted by manifold benefits that emerge for distinct actors. As one would expect, many of the benefits appear for the end users where DES can be installed. Another player that benefits in various ways is the distribution system operator.

> *I see the value added especially when it is possible to take pressure off and stabilize the low voltage grid – more than on end-user side.*—Project manager of a large, publicly funded German pilot project.

Furthermore, widespread DES implementation would provide number of opportunities for new market entrants.

An overview of identified key stakeholders and related private benefits and costs is presented in Fig. 4. Identified actors classified as not being key stakeholders do not appear in the figure.

The findings indicate the danger of emerging situations of positive externalities in the future. As presented above, DES is generally seen as beneficial for society even though a later implementation is not considered preferable earlier than in a few years from now. Low DES diffusion is foreseeable, since benefits are spread over many players. As long as benefits are not concentrated around any one actor, i.e., when private benefits do not outweigh private costs, the omission of the socially desirable action to invest in DES is a likely threat.

> *When always only considering decentralized electricity storage isolated from one perspective then one will not go very far.—I, as distribution system operator do not see a profitable investment. I, as electricity trader, do not see a profitable investment. Then one will not go very far. When considering decentralized electricity storage jointly it is something else. But there are a lot of open questions. Is it allowed? How does it look like? There is still a lot to do in the field of decentralized electricity storage concerning laws and regulations.*—Project manager of a large, publicly funded German pilot project.

6. Findings on measures to foster diffusion

6.1. *Measures to foster smart meter diffusion*

To overcome barriers to wide smart meter diffusion, a set of measures and approaches to foster smart meter implementation were identified. These will now be discussed.

Well-designed legal requirements and regulatory frameworks are seen as an appropriate way to foster smart meter diffusion; these should be clearly defined and free of contradictions, which is not the case at present.

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[6] This benefit must be weighed against energy losses owing to limited electricity storage efficiency.

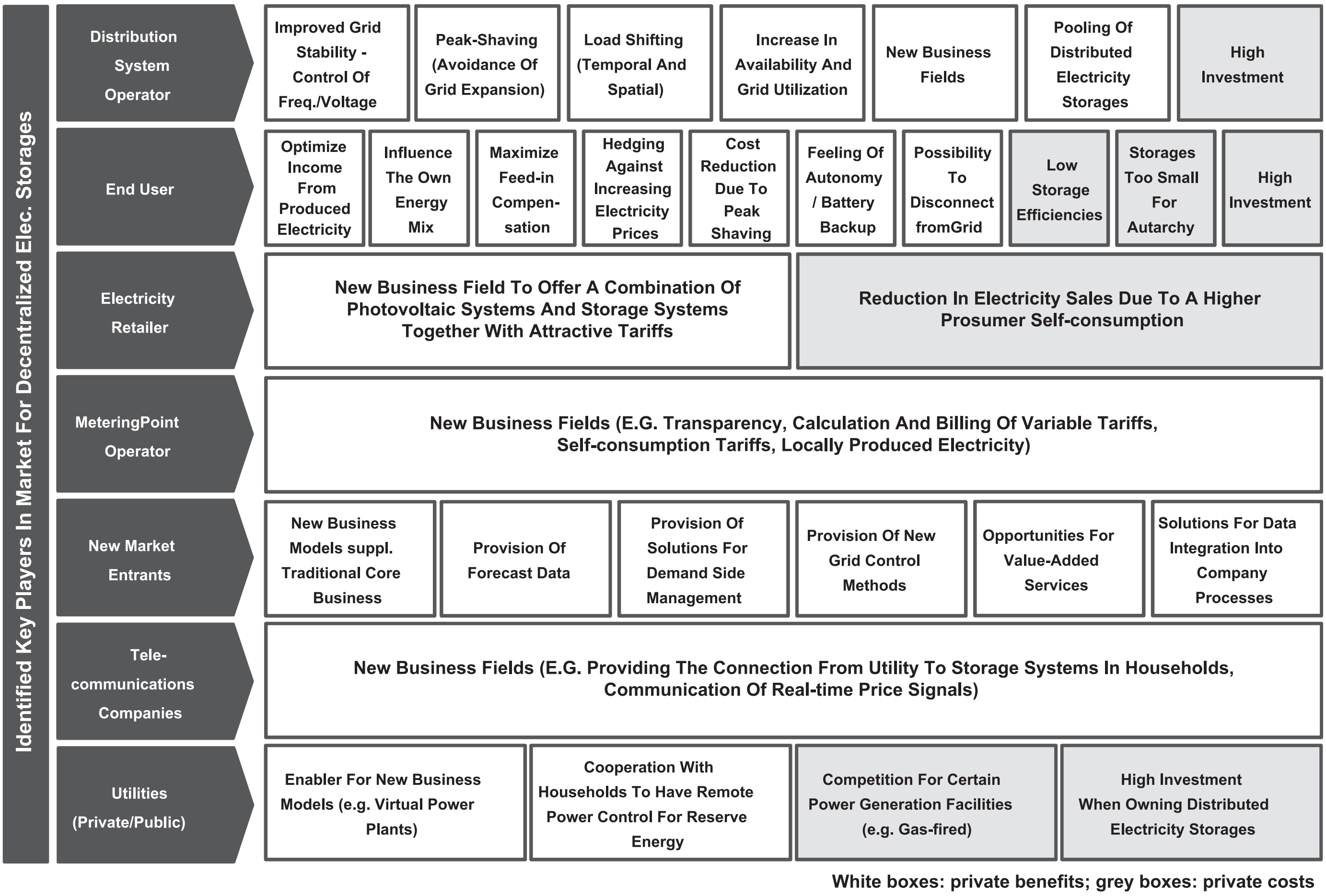

Fig. 4. Key stakeholders in the market for decentralized electricity storage and their private costs and benefits.

The interviews indicated that standardization – for example, of interfaces – is an appropriate way to overcome obstacles. Standards must be defined to enable modular smart meter design, and clear rules for data security and privacy are needed. This would allow changes and supplements to installed smart meters and would thus decrease the risk of expensive replacements.

> *Under the condition that a cost-benefit analysis leads to the result, that we have the wish to introduce smart meters nationwide, regulatory interventions would be necessary.*—Scientist in a leading position in a policy consultancy in the field of technology assessment and energy markets.

We also find that specific loan programs can be used to foster smart meter diffusion. In this context, niche players need easier entry into the market. Companies entering the market with innovative pricing models could be subsidized by the government, and end users can be motivated to acquire a smart meter through receiving subsidies. Smart meters should be offered to the end user for free or at a very low price. Surprisingly, most interviewees did not consider direct interventions through subsidies or tax releases as a useful measure.

> *Subsidies, in the sense I pay something so that one is doing it, what one would not do by oneself, I think, this cannot be the right way.*—CEO of a consultancy specializing in utilities.

Showing customers how they benefit from smart meters – for example, from cost savings owing to lower reading costs, more transparency, recognition of electricity guzzlers as well as lower electricity costs during times of excess energy in the grid – should be highlighted. The insufficient illustration and communication of advantages to end users were mentioned as a crucial weakness.

6.2. *Measures to foster diffusion of decentralized electricity storage*

Measures and approaches to boost diffusion of DES will now be presented. The authors find that monetary incentives can be an effective measure to promote DES installation. Additionally, new price mechanisms to compensate for feed-in and self-consumption of renewably generated electricity as well as time-variable or load-variable tariffs were identified as possible measures. The interviewees often mentioned that further research should be conducted so as to develop more efficient batteries. Another measure is encouraging and boosting producers' own electricity consumption (self-consumption). Wider diffusion would lead to an increase in sales and production numbers, which would reduce costs for DES owing to economics of scale and learning curves regarding production methods. Furthermore, the authors identified that performance-based feed-in compensation can be an appropriate way to foster diffusion. Making compensation (in euro per kW h) dependent on feed-in power makes peak-shaving and the DES usage financially compelling. An incentive could be to provide lower compensation when feeding-in at a higher power level.

> *It is not the business of legislature to substitute the creativity of markets.*—Team leader for the development of a DES system.

Regulatory interventions are seen as an important adjustable screw. Others are more skeptical concerning regulatory interventions.

7. Conclusions and implications

Increasing the diffusion of decentralized RES such as wind or solar energy will lead to a growing amount of fluctuating electricity production. Low-voltage grid stability is threatened if constant demand patterns are met with fluctuating production. Against this background, this study evaluated social benefits of investments in key components of a future smart grid that allow real-time demand adjustments or intertemporal decoupling of supply and demand. The interviewees regarded investments in both components smart meter for AMI and DES as generally beneficial for the society. However, the state of DES is regarded as lagging behind the development of smart meters on both the technological and the business sides. Further research should therefore be conducted in order to improve battery efficiency, decrease costs and develop appropriate electricity tariffs. Furthermore, this study identified key stakeholders in AMI and DES markets. Besides the expected players that are already associated with electricity markets, the investigated new components provide massive opportunities for both telecommunications companies with many of the required core competencies and further new market entrants.

The study revealed manifold costs and benefits for each player. In the case of AMI, most identified benefits were for end users, electricity retailers and telecommunications companies. For DES, most benefits are for distribution system operators and end users. The authors determined that, in total, experts hold that benefits outweigh costs; however, private costs outweigh private benefits. Thus, investments that would be beneficial to society are not made. Hence, a key finding of the authors' analysis is that widely distributed benefits cause situations of positive externalities and thus lead to the omission of a socially desirable deployment of the examined technologies. The authors determined factors and reasons for the low diffusion of smart meters and DES. They also identified and discussed measures to foster the diffusion of both key smart grid components.

This study has important implications for energy market stakeholders and policy-makers. First, industry experts consider well-designed and clearly defined regulatory and legal frameworks as the single most important aspect. To foster investments, legislative authorities must be aware of the abovementioned positive externalities. Two ways to overcome these positive externalities are pooling property rights and concentrating distributed benefits on one actor, or enabling cooperative business models by implementing appropriate framework conditions. Thus, considering the widely distributed benefits, the authors suggest that stakeholders seriously consider the potential of new collaborations. For this purpose, the authors' overview of stakeholders and their specific costs and benefits may serve as a tool for finding appropriate partners for joint projects. Second, direct regulatory interventions such as subsidies or tax releases are currently not seen as the right measure to address slow diffusion. Surprisingly, interviewees supported this point of view, although their organizations would benefit directly from such interventions. Third, especially in the case of AMI, standardization and interfaces are important issues. To avoid replacing technically obsolete smart meters in the near future, modular design is prerequisite, since it allows for future changes and additions. Fourth, advocates of AMI must clearly communicate benefits to end users, since end users seldom know what these are. Fifth, even though most experts do not see a breakthrough for DES within the next few years, implementations under specific conditions might already be economically viable at present. Hence, further research could identify possible niches for applications. Sixth, feed-in tariffs for RES should be designed as power-dependent in order to provide incentives for peak-shaving behavior. Seventh, supportive measures should focus on smart meters in a first step, since – in terms of development—technology has already superseded DES technology. In the long term, a combination of AMI and DES is recommended.

8. Limitations and further research

This study provides new and valuable insights concerning key components of a future smart electricity grid: smart meters and DES. However, there are still some limitations, which open avenues for further research.

First, the authors' results are based on the analysis of 8 qualitative expert interviews. Even though saturation level concerning novel findings was reached, the results could be validated by increasing the sample or choosing another research approach such as expert focus groups. Second, the authors conducted interviews only with German experts focusing on the German electricity market—a pioneering market owing to the facts that Germany is seeking to completely abandon nuclear power within the next few years, and the high and rapidly increasing penetration of intermittent energy production. Thus, future research could validate the results for other countries or regions. Third, because the experts were interviewed in German, the authors had to translate the interviews into English. Although spelling and translations were double-checked, this can be seen as a study limitation. Fourth, the authors exclusively used only qualitative methods. Future research could combine qualitative and quantitative data to validate these results and to quantify positive external effects. Consequently, this study is best viewed as a case study with findings that are applicable to other markets.

A research gap has been identified for the design of variable tariffs concerning both AMI and DES. For example, a deeper understanding of end user responses to different types of tariffs and their resulting use of AMI and DES should serve as a basis for the design of suitable legal and regulatory frameworks. Furthermore, future research can focus on business landscape changes in smart grids. It seems promising to study opportunities for new collaboration between existing players and how a single player can benefit or lose as a result. Because this study revealed opportunities for new market entrants, future research could also examine emerging possibilities and study framework conditions in order to identify factors that foster entrepreneurial activities in the area of smart grids.

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