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What hampers energy system transformations? The case of smart grids

Stefan Muench [a], Sebastian Thuss [b], Edeltraud Guenther [a,c,*]

[a] Chair of Environmental Management and Accounting, TU Dresden, Dresden, Germany
[b] Chair of Political Systems and Comparative Politics, TU Dresden, Dresden, Germany
[c] McIntire School of Commerce, University of Virginia, Charlottesville, VA, USA

HIGHLIGHTS

- Fourteen in-depth expert interviews were conducted and qualitatively analysed.
- We provide a dynamic smart grid definition framework.
- We examine barriers to smart grid technology implementation.
- We provide recommendations to overcome these barriers.

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ABSTRACT

Energy systems are undergoing significant change. Many countries have ambitions to increase the share of renewable energy in their energy mix. This development entails the challenge of incorporating an increasing amount of volatile energy supply and a higher number of energy providers on distribution grid level. The smart grid could be a solution for this challenge. However, the implementation of smart grid technologies is rather slow. In this paper, we examine which barriers exist for the implementation of smart grid technologies. Fourteen in-depth expert interviews were conducted and qualitatively analysed using the grounded theory approach. First, a dynamic definition framework of the term “smart grid” was developed that incorporates contextual factors. Second, barriers to the implementation of smart grid technologies were gathered. We identified (1) cost and benefit, (2) knowledge, and (3) institutional mechanisms as barrier categories. Third, policy implications were derived. We recommend (1) the acceptance of a diversity of solutions, (2) the acceptance of incremental change, (3) the implementation of a stable regulatory framework, (4) the alignment of interests of individual market participants with the entire system, (5) the definition of a suitable scope of regulations, and (6) the collection of problem-specific information.

1. Introduction

Energy systems are undergoing significant change. The call for renewable energy has triggered two major developments. First, there will be an increasing amount of volatile energy supply (Kranz et al., 2010:1; Wissner, 2011b:2510; ZVEI, 2012:3). Second, the number of energy providers on the distribution grid level will increase (Mattern et al., 2010:2; Verbong et al., 2013:119; Wissner, 2011b:2509). Both of these developments are challenges that can put the stability of energy transportation systems at risk (Verbong et al., 2013:119; World Economic Forum, 2010:12). A solution for these challenges is the implementation of smart grid (SG) technologies to match supply and demand (Kranz et al., 2010:1; Mah et al., 2012b:133; Verbong et al., 2013:117–119).

Changing environments demand organisations to adapt to new circumstances to remain competitive (Pool and Van den Ven, 2004). The case of SGs is particularly interesting because they are praised as a solution for the above mentioned challenges. However, the implementation of SGs is rather slow (Römer et al., 2012:487). From our literature research, the most relevant stakeholders for the development of SGs were derived. These are (1) policy-makers, (2) smart grid technology providers, (3) distribution grid operators (DGOs), and (4) end users (e.g. World Economic Forum, 2010:42–44). We subsumed the regulation authority under policy-makers since their positions are largely identical with those from governmental institutions. The stakeholder DGO also comprises metering service providers and metering point operators. End users include market participants that only consume, only provide, or consume and provide energy, i.e. consumers, providers, and prosumers. In this

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[*] Corresponding author. Tel.: +49 351 463 34313.
E-mail address: ema@mailbox.tu-dresden.de (E. Guenther).

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paper, barriers are defined as disruptive factors “that may decelerate, slow down or even block” (Günther and Scheibe, 2006:63) the implementation of technologies. In fact, change processes are likely to entail barriers (Argyris, 1993:31–35; Battilana and Casciaro, 2013:819; Post and Altma, 1994:66–69; Schimmel and Muntslag, 2009:399–400). An analysis of general barriers to change is not sufficient in the case of SGs because barriers are context-specific (Arvanitis and M’henni, 2010:237; Blindenbach-Driessen and van den Ende, 2006:545; Fagerberg et al., 2012:1177–1178; Wu, 2012:489–490), and the energy industry faces distinct challenges. First, with an increasing amount of required information and communication technology, the traditionally long-term oriented energy distribution sector (Cook et al., 2012:4–6; Cramton and Ockenfels, 2012:115) is being confronted with much shorter innovation cycles (Eschenbaecher and Graser, 2011:374). Second, energy grids are traditionally geared to cost effectiveness while at the same time grid operators are now expected to implement innovations (Wissner, 2011b:2516). Third, the design of an energy system is heavily influenced by political decisions (Buhl and Weinhold, 2012:179; Pollitt, 2008:706). However, previous literature is rather fragmented, i.e. limited to certain stakeholders, and does not include a comprehensive analysis of barriers.

We face the additional challenge that no universal vision of a SG exists. For example, the German Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway made an implicit attempt to define smart grid by a division between smart grid and smart market (Bundesnetzagentur, 2011:11–14). Whilst this definition provides a rough distinction between the capacity of an energy grid (in kW) and the market (in kW/h), the actual characteristics of the hardware can be manifold. This problem has been approached with different ways of defining a SG. However, these approaches are often static and do not take into consideration the uncertainties regarding the characteristics of the future energy system which, in turn, influence the design of SGs.

From the two above mentioned research gaps, we derived corresponding research questions (RQs). First, uncertainty about the future energy system is omitted in the SG definitions. Hence, RQ1: “How can the term smart grid be defined?” was formulated. Second, no detailed analysis of barriers to SG technology implementation was identified in the previous literature. Thus, two research questions were derived to inquire into this topic. RQ2.1: “Which barriers exist for the implementation of SG technologies?” addresses the barriers for SG technology implementation. We also investigated recommendations to overcome these barriers with RQ2.2: “How can barriers to the implementation of SG technologies be overcome?”

This study is structured as follows: In Section 2, we provide an outline of the empirical basis of this study and our research approach. In Section 3, we present the results of the expert interviews. In Section 4, we discuss the findings of our analysis and compare them to the findings of existing literature. In Section 5, we present the conclusions of our analysis, implications for policymakers, limitations of our study and potential for future research.

2. Material and methods

Theory building from case studies is an adequate research procedure (Eisenhardt, 1989:534; Mayring, 2002:41–46; Yin, 2009:5–14) for the case of the barriers to SG technology implementation. This approach has already been applied in the investigation of other SG related issues (e.g. Mah et al., 2012b:134; Römer et al., 2012:489; Wissner, 2011b:2510). Grounded theory hereby forms a suitable and well-tested collection of research methods whose goal is to generate abstract concepts and postulates from primarily descriptive representations of social phenomena (Strauss and Corbin, 2008:50–53).

Because the focus for this study laid on the generation of qualitative data that can be the basis for following quantitative analyses, experts were selected using theoretical sampling (Eisenhardt, 1989:537; Matus et al., 2012:10893; Sandelowski, 1995:180). We chose experts evenly from the fields of (1) research, (2) industry, and (3) associations and political institutions. Following the same approach, the covering of extreme positions (Pettigrew, 1990:275–276) has been considered. In the selection of experts, an advocacy coalition approach (Sabatier, 1998) was used to identify experts with diverging schools of thought in each field. Table 1 provides an overview of the experts and their professional backgrounds. We conducted interviews until theoretical saturation (Sandelowski, 1995:181; Strauss and Corbin, 2008:263) was reached. In this paper, information from interviews is referred to by the number (#*n*) in the left column. Fourteen in-depth expert interviews were performed, either personally or via telephone, by two interviewers between April and August 2013. For this study, we selected one country of origin to avoid biases due to different legal backgrounds; a German context was ultimately chosen because the nuclear phase out and high amount of renewable energy make it an eminent case. We refer to Römer et al. (2012:486) in their argument that such results can provide valuable insight for other countries.

The interviews were conducted on the basis of a semi-structured interview guide. Because different approaches to defining SGs could be identified during the literature research, no working definition was provided to the interviewees in advance. In accordance with established research approaches, the interview contained three predefined research topics (Eisenhardt, 1989:536). First, the influence of different energy system transition pathways on the energy system design was derived from previous research. The validity of this construct for the case of SGs was critically inquired into during the interviews. Second, barriers to SG technology implementation were collected. Third, recommendations to overcome these barriers were gathered. Open questions were formulated to obtain unbiased answers (Reja et al., 2003: 174). The guide was validated using a double cognitive pre-test, i.e. paraphrasing and think aloud interviewing (Collins, 2003) with experts from each chosen field.

Table 1
Overview of experts.

	Research	Industry	Associations and political institutions	Background
#01	✓			Power engineering
#02	✓			Power technology and economics
#03	✓			Energy markets
#04	✓			Information and communication technology
#05		✓		Business development
#06		✓		Chief Executive Officer of SG technology provider
#07		✓		Sales
#08		✓		Communications
#09		✓	(✓)	SG division
#10		(✓)	✓	Power engineering
#11			✓	Energy systems
#12			✓	Energy technology
#13			✓	Energy systems
#14			✓	Energy sector
Total	**4**	**5**	**5**	

Note: More specific descriptions of expert backgrounds are not shown to ensure anonymity.

The interviews were recorded and transcribed verbatim (Mayring, 2002:89–90). The analysis of data was conducted by two authors simultaneously to ensure a higher degree of sensitivity (Strauss and Corbin, 2008:33–35). Following the inductive approach of Glaser and Strauss (2009) for case study research, four procedural steps to build theory were followed. In the first step, concepts were formulated during the open coding process by labelling phenomena (Mayring, 2002:103–104). In the second step, categories and sub-categories were derived that relate codes to each other. In the third step, this categorisation was refined by axial coding, which embeds identified subcategories along an analytic axis. In the fourth step, patterns and an integrative theoretical storyline, which all categories are related to, were derived during what is referred to as selective coding (Strauss and Corbin, 2008:106–115). It is acknowledged that coding can be subjective (White and Marsh, 2006:35). The use of memos for each code and the reconciliation of conflicting codings via communicative validation (Kvale, 1995:30–32) ensured a high credibility of the derived categorisation.

As suggested by Eisenhardt (1989:545–546), we contrasted our findings with existing literature and theory in Section 4. We compared our definition and identified barriers with previous research which we gathered in a systematic literature review. Literature was searched for in bibliographic databases (EBSCO Information Services, Web of Knowledge), the search engines of large publishers (Elsevier/ScienceDirect, Emerald, SpringerLink, Wiley), and public search engines (Google Scholar, Social Science Research Network). We used the term smart grid ("smart grid", "smart-grid") combined with synonyms for barrier ("hurdle", "barrier", "impediment", "obstacle", "hindrance") as search words. In a practical screening, we applied the inclusion criterion that a paper must discuss barriers for the implementation of SG technologies. In total, our search yielded 117 studies (without duplicates) of which one was not available and 73 did not pass the practical screening. Hence, 43 papers were included in our literature analysis. We compared our identified structural barrier patterns, i.e. findings from the fourth procedural step to build theory, with a set of existing organisational theories to find out whether an existing theoretic framework can explain these patterns. This set was derived from a comprehensive list of adaption and selection theories presented by Lewin et al. (2004).

3. Results from expert interviews

In this chapter, we present statements derived from expert interviews. Comments from the authors are shown in italics. This chapter includes findings from the first and second procedural steps to build theory.

3.1. Smart grid definition

The basic directional distinction regarding the design of future energy systems can be identified by highlighting its degree of centrality (Bae and Kim, 2007:785–787; Bayod-Rújula, 2009:377–381; Mautz, 2012:163–164), which is still uncertain. The consideration of this fact in a definition of the term SG is important, yet neglected. With regards to RQ1: "How can the term smart grid be defined?", the term itself was criticised for being too blurred (#13), overly fashionable (#10), or appearing as a purpose on its own (#02; #08; #09; #10; #12; #13). A differentiated definition is therefore of high importance for a goal-oriented debate (#02). *In this section, we present expert statements regarding (1) the influence of an energy system's degree of centrality on the design of SGs and (2) definition criteria for SGs.*

3.1.1. Dependency on degree of centrality

A future energy distribution system should be a solution that serves the entire energy system; its characteristics are therefore intermingled with the energy system's future development paths (#03; #12). *As discussed above, the basic directional distinction regarding the design of future energy systems is their degree of centrality.* A highly decentralised energy concept, for example micro grids (#01) and a high number of small scale feeders would ask for a higher pervasion of SG technologies (#02; #05; #09; #12). Additionally, a plurality of technology providers would likely enter the market in this case (#13). In a moderately decentralised energy concept, a stabilisation of the energy distribution system would be reached (#05) without consequent fragmentation into island grids (#01). *A medium pervasion of SG technologies would be the result.* A highly centralised energy concept, for example large scale energy provision and transmission, would reduce the necessity of the energy grid to adapt its structures (#06; #09; #12). *Hence, a lower pervasion of smart technologies would be necessary.*

A general interrelation between the degree of centrality and the pervasion of SG technologies is seen (#02; #05; #06; #09; #12). However, the economic meaningfulness of vastly decentralised or even self-sufficient regions is doubted for the German case (#02). A reason for this doubt is that transmission line extensions are comparatively cheap (#04). From a macro-economic perspective, highly decentralised solutions would only be profitable if affordable storage technologies or very large distances were given as contextual factors (#13). Additionally, the traditionally grown structure of the interconnected energy systems could hinder such a development due to a technological and regulatory lock-in of transmission grid extensions (#06; #11). With regard to SG technologies, it has been stated that they will be needed in any case because of the already foreseeable path of decentralisation (#01; #02; #05; #08; #12). Given this surrounding area of conflict, experts favour an optimal mix between possible central and decentral energy pathways (#05; #07; #12). Hence, the according SG design can be considered as a result of future requirements of the energy system rather than a purpose on its own (#02; #08; #10; #12; #13).

3.1.2. Smart grid definition

*In our definition of the term smart grid, we distinguish between its intension, i.e. unique features, and its extension, i.e. coverage or actual design (Blockeel and De Raedt, 1996:379). We define SG as an energy distribution system with the unique features (**I1**) to allow functional interaction of relevant market participants with the implementation of modern technologies such as information and communication technologies, (**I2**) to provide the capacity (in kW) that enables smart market applications (in kW/h), and (**I3**) to ensure the stability of distribution grids by securely connecting a large number of small points of intermittent consumption and production. Its actual design depends on (**E1**) whether transmission line expansions or the implementation of smart grid technologies is emphasised, (**E2**) which energy carriers will be included in the future energy system, and (**E3**) which users are suitable for the inclusion in a SG. In the following, we describe how this definition was derived from the interviews in greater detail.*

I1: Enable functional interaction. A SG covers the technological upgrade of energy grids with information and communication technology or simply the latest electro technology; (#02; #03; #04; #06; #09). This upgrade is to enable functional interaction of all relevant participants within the entire energy system (#01; #09; #11; #13). A SG provides information and prognoses (#04; #05; #07) about the overall system's status (#08) based on its individual components (#11) and enables remote-controlled (#09) and automated operation (#04; #09), which also includes curtailing feeders (#01; #14). This way, SGs aid to optimise the balancing of supply and demand (#10; #13).

I2: Distinction of smart grid to smart market. It has been noted that the ability to integrate market participants into the system is a necessary condition (#01; #11). However, from an analytical perspective, a clear distinction between SG and smart market (#01; #02; #03; #07) is necessary. In the first case, the stabilising and enabling function of the grid is in focus. In the second case, individual business cases, such as demand side management or virtual power plants, are emphasised (#05; #10). *Such a distinction was introduced by the German Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (Bundesnetzagentur, 2011:11–14)* and was supported by interviewed experts (#01; #03; #07; #10; #12). By definition, the SG (unlike the smart market) is therefore strongly bound to regulations, particularly with regard to security standards or financial incentives (#07).

I3: Ensure system stability. The SG is a technological upgrade of the classical distribution grids. These are currently changing from a mere distribution into a feed-in system that must integrate a high number of fluctuating feeders (#02; #05; #08; #11). Distribution grids were traditionally designed according to a rather simple maximum load scenario of electricity demand (#01; #08). However, new challenges of operating distribution grids need remedying (#01; #09). These are most notably the stability of voltage (#01; #02; #08; #09; #12) and frequency (#01) and the automated management of supply and demand (#01; #14). Addressing these issues puts DGOs in a position to overtake the responsibilities for ensuring the stability of the entire system (#01; #04; #05; #11; #12). As a consequence, the definition of a SG is closely linked to the upcoming challenges for DGOs (#12).

E1: Smart grid or transmission line expansion. The interpretation that smart technologies might pose an alternative to the regional interconnection via high-voltage transmission grids has been mentioned (#06; #07; #12; #13). This line of thought also includes investments in non-information and communication technologies, i.e. primary technologies such as the latest electro technology (#06; #12). Transmission line expansions can be limited by installing SG technologies in distribution grids (#01; #02; #06; #07 #12; #13). In addition, it has been noted that both SGs and an extension of transmission lines will be required (#02; #07; #12). *In summary, a higher amount of avoided transmission lines necessitates a broader range of SG technologies.*

E2: Included energy carriers. First, the interconnection between smart technologies and the e-mobility sector might form a field of application that extends the boundaries of today's electric grids by adding flexible options for storage and load via intelligently charging electric vehicles (#02; #07; #14). Second, hybrid grids that provide the intelligent coupling of electric grids and chemically stored energy, for example power-to-gas, could merge energy infrastructures to optimise and stabilise the overall energy system (#04; #05; #08; #10; #11). A substantial share of energy is transported in a gaseous way, which is why a SG would also serve as the integration and coordination of these options and therefore has the character of a hybrid grid (#05; #06). Third, stronger interlinks between the heat and electricity markets could be a consequence of the energy transition. Here, small-scale combined heat and power plants that are power regulated via automated processes could be facilitated through SGs (#07).

E3: Target users. The experts were inconsistent regarding a nationwide smart meter roll out (#01; #03; #08; #13; #14). Generally, all users with load shifting potential are relevant for the SG (#09; #13). However, several experts state that the integration of individual households is economically not rewarding (#03; #06; #13; #14) and offers only limited load shifting potential (#01; #13). Exceptions are idealistic users (#14) and load shifting potential in heating and cooling (#09). Experts consider the integration of industrial users as potentially rewarding (#02; #03; #06; #13). Exclusions are large industrial users who are connected to the transmission grid (#06) and small businesses, such as crafts or retail, that lack flexibility (#01). A few large industrial users are already integrated as abandonable load (#02; #14). However, many industrial users have not discovered this business model because they perceive the involved transaction costs for load shifting as too high (#06; #13).

This section highlighted the influence of an energy system's degree of centrality on the design of energy distribution grids. Furthermore, it presented intensional and extensional definition criteria for the term SG. A discussion of the dependence of these definition criteria on each other and on the degree of centrality is presented in Section 4.1.

3.2. Barriers to smart grid technology implementation

With regards to RQ2.1: "Which barriers exist for the implementation of SG technologies?", impediments to the implementation of energy technologies were inquired into. In the following, we related barriers to the stakeholders identified in our literature research, i.e. (1) policy-makers, (2) technology providers, (3) grid operators, and (4) end users.

3.2.1. Policy-makers

Incentive regulation hinders innovation. An incentive regulation should simulate a competitive environment whilst enabling profits from innovations (#09). Innovations are refunded according to the German incentive regulation (#12). However, if a DGO has to provide new services, as is the case with some SG relevant technologies, related innovation costs are not necessarily covered (#08; #09). This situation led to refused reimbursements of investment costs in the past (#04; #12; #13). In fact, there is a high pressure to ensure relative cost efficiency of energy transmission and distribution networks (#11), *where certain cost categories are benchmarked and poor performance leads to cuts in refunds (Bundesregierung, 2007)*. When those cost categories are not directly comparable, the problem of distorted refund ratios for different distribution grids arises (#12). Another barrier is the long payback period of investments in SG technologies because reimbursements are usually delayed (#06; #10). DGOs face pressure from shareholders such as municipal or private owners who tend to be rather short term oriented (#12).

Regulations allow no planning security. No clear assignment of roles is defined in the transformation to a smarter energy distribution system. It is not yet determined (1) who has to pay for SG technologies (#03), (2) who shall profit from it (#03; #05), (3) who is responsible for the construction of an energy information infrastructure and who merges data of an intelligent energy distribution system (#13), (4) which parts of the energy distribution system should be more intelligent (#14), and (5) who operates a SG (#05). However, to be able to reasonably discuss SG characteristics, a clear political and regulatory framework has to emerge (#14). In addition, discussions are held on a high level of abstraction (#14) and the progression towards more concrete topics is slow (#13). Furthermore, important regulations in the energy industry, for example on the nuclear phase out (#06) or the feed-in tariffs (#05), have not been consistent in the past. This contrasts with the rather long term planning in this industry, where capital equipment usually last 20 years or even longer (#06). A disturbing factor is the rivalry between ministries, which adds more uncertainty regarding future policies (#04; #08).

Highly complex information regarding the energy system. The exact appraisal of hybrid energy systems that have a high potential to supplement existing technologies is too complex (#11). Hence, policy-makers are struggling to fully comprehend the actual benefits of a smarter energy grid (#08). Furthermore, the complexity of energy-related regulations is high. A key question is how to integrate renewable energy in the energy system. This integration is a complicated matter, especially in the light of the complex German Renewable Energy Act (#11). Distribution grids in Germany have very different designs and cannot necessarily be put into one basket. Differences are due to diverging shares of renewable energy feed-in (#11; #14), levels of know-how (#12), sizes (#05), and financial resources (#06). Regulations must account for some of these differences (#14). Because distribution grids are regulated areas, the challenge is to digest all available information and make informed decisions (#13).

Slow adaptation to the new situation. Current energy regulations were initially not issued to promote technological innovation. During an episode of energy system liberalisation in Germany, energy generation, transmission, distribution, and supply were unbundled, and the aim of the incentive regulation was to maximise efficiency and keep network expenses at a minimum level (#01; #08). Regulatory authorities adhere to this target and attempt not to create new subsidy cases (#11). There is some inertia in regard to the adaptation of existing policies and amendments (#01; #04; #12). An innovation factor is not sufficiently considered in the incentive regulation (#08; #09; #11; #12). DGOs can reclaim only a part of their research and development expenses (#06; #12) and there is a delay in the refund due to a five-year assessment period (#01; #06). Currently, focus rests on low network costs. However, a turn towards rewarding not only cost efficiency, but also good change management toward an intelligent energy distribution system would be desirable (#01).

Principle-agent problem. When making decisions, politicians are faced with (1) the preferred option of their own party members, (2) the preferred option of potential voters, and (3) the preferred option according to concrete *political, economic, social, technological, ecological and legal* conditions. Preferred outcomes according to these stakeholders are not always in accordance (#01). Political decision makers tend to focus on the interests of their own party and potential voters (#10). *This can lead to poor decisions for energy policies which greatly affects highly regulated industries such as the energy distribution sector.*

3.2.2. Smart grid technology providers

No perceived business case for smart grid technology development. SG technology providers have invested heavily in the development of modern technologies for energy grids (#06; #09; #11; #12). However, despite successful pilot projects, a large scale implementation has not yet started and requires more time. This gap between research and development expenses and sales from new technologies is a problem (#06). In addition, the transferability of technologies that has been developed for Germany to other countries is dubious (#13). Some countries may not feel the need to invest in SGs because conventional flexible energy technologies are preferred to renewable energy (#06).

Uncertainty regarding the development of the energy system. Technology providers are acting in a rapidly changing technological environment. It is difficult to stay up to date regarding new technological developments and, hence, to decide which technology should be supported (#13). Similar to policy-makers, SG technology providers do not know which form our energy system will take in the future (#13). This leads to the situation that they are uncertain about which technologies should be further developed. It is difficult to assess the concrete design of new technologies when it is unclear whether they will be needed at all (#11). *We conclude that while there is always uncertainty in technology development, the high impact of the future energy system's design on SGs influences strategic planning in this sector.*

High complexity of smart grid technologies. Many research and development projects are being performed around the SG. This research leads to a variety of possible SG solutions that do not fit together seamlessly (#02). A further impediment is the missing experience with these new technologies and the resulting uncertainty about how they operate under real conditions (#05). *For energy distribution systems, the implementation of a new technology, on which limited experience is available, might cause system instabilities.* Missing standards can be considered as a threat to going downmarket (#01). There are over 100 different protocols for smart meters (#06). Compared to already existing energy technologies with well-established standards, SG technologies must catch up in this respect (#02). Furthermore, different distribution grid designs pose a problem for technology providers because no standardised product can be developed so far (#12).

Uncertainty about data security standards. Related to an outstanding exact regulation, security requirements of smart meters are not yet fully determined (#03; #08). *The Federal Office for Information Security is currently drafting a guideline for security requirements of smart meters (Bundesamt für Sicherheit in der Informationstechnik, 2013) which is still being finalised.*

Poor adaptation of the organisational structure. The combination of formerly distinct departments, for example hardware and software development, poses an organisational challenge to providers since the working culture varies strongly between departments (#08; #09). The increased complexity of smart energy transportation technologies calls for more support from technology providers for DGOs (#02; #08). This transformation from a provider of technologies toward a provider of solutions is a cultural challenge for technology providers (#08). Whilst some companies have been enforcing this transformation for quite a while (#04), others still must adapt to this situation (#08).

3.2.3. Grid operators

No perceived business case for smart grid technology deployment. DGOs have a disadvantage if energy-saving technologies are rolled out in the current energy only market (#05; #07). Furthermore, the possibility of passing on costs such as re-dispatch expenses make certain investments financially not interesting on a micro level, whilst they would be greatly beneficial on a macro level (#03; #06). In contrast to other countries, certain context factors on the micro level, such as power theft or short meter reading intervals, are not relevant in Germany (#06). Finally, there has not been a success story yet (#11). This may be because early innovators face the threat of being considered cost ineffective (#01) or a shortage of funds to test new technologies (#12).

Missing experience with smart grid technologies. The upgrade of distribution grids with information and communication technology makes an energy system more complex and perhaps also more vulnerable (#13). In addition, only a small amount of experience is available about the technological parameters of some of the proposed innovations (#05; #11; #13). This lack of experience complicates an evaluation of a certain solution and adds uncertainty to the grid management (#02). Larger DGOs have the capacity to build up the necessary technological know-how. However, this capacity is not available for many smaller operators (#02; #05) who reduced staff levels due to cost pressures (#12). DGOs must build up the know-how to be able to cope with the new requirements (#04; #05; #09; #12, #14). Another challenge is the heterogeneity among distribution grids. *There are over 800 DGOs in Germany (Bundesnetzagentur, 2013)* that have diverging requirements for grid technology (#12). However, a coordinated technology strategy is required for a trans-regional intelligent energy distribution system (#05).

Poor adaptation of the organisational structure. DGOs are confronted with a changing environment (#09). Whilst most operators are aware that the electricity industry will change fundamentally, this development is still ignored by some companies (#09). Some DGOs are still struggling with the thought of combining information and grid technologies (#04). They must get used to much shorter innovation cycles (#01) and shift their priority from cost effectiveness toward innovation capacity (#09). This new culture contradicts the way they have been operating in the past. Top management and employees are reluctant to adapt their way of working (#02). This reluctance is a particular challenge for the traditionally blue-collar intensive workforce of DGOs (#09).

No information infrastructure exists. A crucial prerequisite of a smarter energy grid is an energy information infrastructure, which does not yet exist (#04; #09). In comparison to the existing internet infrastructure, the energy information infrastructure is critical and an outage might, depending on its size, be much more damaging than would be the case for the breakdown of the internet. Hence, the energy information infrastructure requires high safety standards and constant availability of its critical parts (#09). This yet missing information infrastructure is considered as a structural deficit that must be overcome so that the implementation of SG technologies can be successful (#09).

Principal-agent problem. Technological equipment in the energy industry has long life spans of 20 years and more (#06). Investments in SG technologies will pay off over a comparatively long time period (#02). However, managers tend to think short term because their success in a company is rather tied to operational performance (#10).

3.2.4. End users

No perceived business case for smart market applications. End users are not aware of the potential applications and benefits of SG technologies (#03; #08). Households do not appreciate their high base load energy consumption (#07). Even if they wanted to save energy with smarter appliances, the savings potential would not be high and the target group would rather be idealists (#03; #14). Regarding small industrial end users, the cost of SG technologies is likely to exceed the potential benefits. Only businesses with high energy consumption can profit from the SG (#13).

Reduced comfort. The shift toward supply-side oriented energy consumption means that users are incentivised not to use energy when they want to but when enough energy can be provided (#07; #10; #13). Experts doubt whether SGs can change fundamental use patterns (#06; #10). Pilot projects have demonstrated that the information provided by smart meters has been considered only for a short period of time. Soon, users returned back to former behavioural patterns (#05; #06). Furthermore, smart technologies are perceived to make already complicated lives even more complicated (#13).

Perceived threat of privacy and data security. *Smart meters collect and transmit more information than the traditional Ferraris meters.* A complex issue is how to treat the collected data in terms of privacy and data security without unsettling end users (#05; #11; #13). In fact, end users and consumer associations are sceptical in regard to the collection and transmission of consumption data (#08).

This section provided a comprehensive overview of barriers to the implementation of SG technologies. A categorisation of these barriers and the analysis of structural barrier patterns are discussed in Section 4.2.

3.3. Recommendations

With regard to RQ2.2: "How can barriers to the implementation of SG technologies be overcome?", recommendations were sought and are presented as follows.

A) Accept a diversity of solutions

No universal technological or business solution should be adhered to as a blue print because a variety of solutions may fit individual contexts (#03). The existence of parallel solution possibilities is rather a starting point towards an optimal energy distribution system and should not be hindered (#08; #14).

B) Accept incremental change

The implementation of fundamental changes in the energy industry requires long time periods (#10). The development of a master plan seems to be impossible for a complex matter such as an intelligent energy distribution system (#13). Furthermore, decisions leading to irreversible changes that could obstruct future perspectives should be avoided. Hence, experts advise against aiming for a final solution straight away but instead suggest to incrementally move towards an intelligent energy distribution system (#09; #10; #12). A slower pace of the energy turnaround could allow a more comprehensive assessment of this complex matter (#06; #10; #13).

C) Adapt to the new situation

To cope with the changing environment, companies should adapt their organisational structures. Building cross-sectional sub-units could overcome internal blockades and trigger learning effects (#09). Market players also must build up new relevant know-how. If an organisation does not have the capabilities to do this on its own, co-operations, outsourcing, or contracting external knowledge are possible solutions (#04; #14). Furthermore, hiring personnel from other industries might help to accelerate this process (#01). On the employee level, new personnel must reflect the changed information and communication technology-driven business profile (#09). Another issue is the implementation of an information and communication infrastructure. A secure and permanent connection for each household is necessary (#09).

D) Create a stable regulatory framework

A reliable regulative environment for all market participants must be created. Regarding the transition of energy distribution systems, general questions must be discussed and clarified. The result should include a clear distribution of market roles and system responsibilities (#14). On this basis, an integrative legislative framework should be established (#09; #10; #11; #12). Once these essential decisions have been made, a regulative self-restraint that excludes fundamental changes is suggested to follow. Such regulation would serve to create stable investment conditions (#12). However, as a learning law, the regulative framework must institutionalise learning-effects to adapt to new developments without being challenged in its substance (#09).

E) Create value added benefits for market participants

On a micro level, a favourable environment for SG technologies would be supportive. The aim should be to foster an environment that triggers a virtuous circle (#05). First, SG technologies that are attractive to users must be introduced (#03; #04). Once there is a successful first mover, other market participants will follow (#08). Second, profitable investments in innovative technologies should be made possible (#11). It has been mentioned that this is already the case (#14). However, it has also been stressed that new areas of responsibility of DGOs call for better refund of, for example, software (#08; #09). Furthermore, shorter reimbursement periods were mentioned as possible enhancements (#06). On a macro level, it is desirable that the incentive regulation attracts investments in favour of the overall system. One suggestion is to offer secured public financing of innovation projects, yet with a pre-implemented decrease of the subsidies (#10; #12). *A crucial point is to align the interests of micro and macro levels. One possibility is the amendment of the incentive regulation for DGOs to also include innovation capacity in the benchmarking process.* Furthermore, the decoupled market mechanisms and network stability issues (#02) should be interlinked more closely. This interlinking could be performed by subsidising demand response mechanisms (#08; #13) or innovations such as virtual power plants (#08).

F) Define suitable scope of regulations

Energy grids are a regulated area and are bound to political decisions (#13). In this context, it must be decided to which extent the energy sector should be regulated and, hence, to which extent the risks of investments should be overtaken by the government (#05). While a grid development plan for distribution systems is considered as a solution (#12), experts also warn that such a step would resemble overly excessive regulation (#02; #05).

G) Obtain suitable information

The active procurement of information by legislators is considered to be crucial to provide a sound legislative framework (#05). Cost-benefit analyses should be conducted to identify worthwhile technology options (#12; #13). In doing so, the gathered information should be free of ideological influences, which is currently not always the case (#10). In fact, the already existing desire of politicians to be informed and make fact-based decisions was mentioned (#14). As a part of that desire, concrete solutions need problem-specific knowledge to reduce the abstract level of the current discussions (#14).

H) Provide understandable information

Market participants and policy-makers must communicate the need for and benefits of SG technologies to reach a higher level of public support (#08). Especially in regard to individual users, communication must be sober and unemotional (#10), yet be aware of the irrational components that complicate the discourse (#10). Private users should be taught about the advantages of SG technologies (#07). Industrial users are not yet fully aware of the economic benefits of smart market applications, such as selling flexibility (#02; #13).

This section provided an overview of recommendations to approach barriers to the implementation of SG technologies. An overview of which recommendation could be used to tackle specific barriers is presented in Section 4.3.

4. Discussion

This chapter includes findings from the third and fourth procedural steps to build theory, i.e. the analytical alignment of categories and the identification of patterns. Furthermore, our findings are compared to existing literature and theories.

4.1. Smart grid definition

A SG is the solution to the challenges arising in the course of the transition of the energy system. The solution to these challenges, in turn, depends to a large extent on the energy system's *degree of centrality* (Fig. 1). An intensional approach defines the unique features of the SG. These are rather static and related in the respect that they are different manifestations of a common cause, i.e. a requirement of the energy system transition. An extensional approach defines a SG's actual borders. These are highly interlocking and depend on the energy system's path of development. For example, a notable reduction of new transmission lines would ask for a broader range of SG technologies. However, the inclusion of energy carriers other than electricity or energy storages could also reduce the extension of transmission lines (#06; #07; #12; #13). Whilst some assessments on energy grid requirements have been published (acatech, 2012; Deutsche Energie-Agentur, 2012; Gerbert et al., 2013), the actual design of a SG is highly uncertain. The mixture between *smart grid and transmission line expansion* is unclear. Another example is the uncertainty about intelligent interfaces with different *included energy carriers*.

Table 2 gives an overview of existing definitions from SG barrier literature. Existing definitions include (1) *definitions via requirements*, (2) *definitions via applied technologies*, (3) *definitions via desired applications*, and (4) the statement that *no clear definition* of SG is possible. We also compared the SG definitions that were derived from our systematic literature review with those from various SG-relevant organisations (e.g. Electric Power

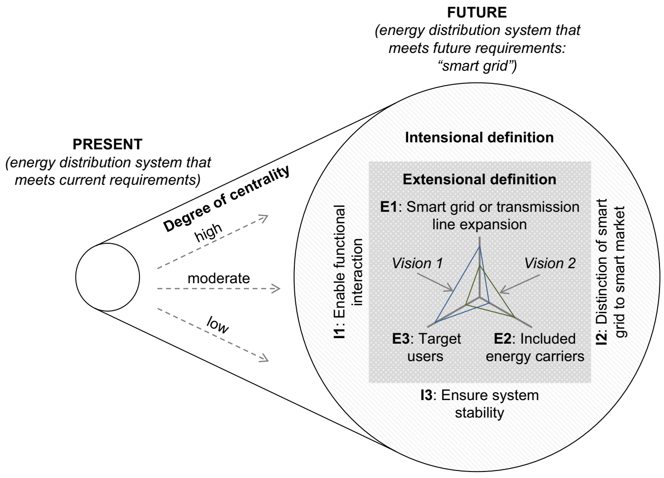

Fig. 1. Smart grid definition framework.

Table 2
Overview of smart grid definitions from previous literature.

Source	Definition
Definitions via requirements	
Curtius et al. (2012:63)	"Intelligently integrate the actions of all users connected to it" (derived from Smart Grids European Technology Platform, 2010:6)
Deblasio (2010:16)	"More efficiently manage peak demands, subvert transmission overloads and keep power flowing"
World Economic Forum (2010:8)	"A digital, self-healing energy system […] enabling end-user energy management, minimizing power disruptions and transporting only the required amount of power"
Definitions via applied technologies	
Cook et al. (2012:5)	"Comprised of a "smart meter" at the customer's premise, a communications network between the smart meter and the utility, and a "meter data management application" (MDMA) at the utility"
Daoud and Fernando (2011:54)	"Advanced Metering Infrastructure (AMI) accompanied by substation and distribution automation services and enhanced distribution and outage management"
Wissner (2011b:2510)	"[Several] developments call for a new approach to operating the power system. A means to do this is to use ICT [information and communication technologies]"
ZVEI (2012:6)	"Integration and management […] by means of intelligent information and communication technologies"
Definitions via desired applications	
Cook et al. (2012:5–6)	"Applications that will support "plug-and-play" technology in the future, Home Area Network technology and the Demand-Response programs"
McDaniel and McLaughlin (2009:75)	"Track usage as a function of time of day, disconnect a customer via software, or send out alarms in case of problems"
Wissner (2011a:19)	"Match generation and demand more efficiently, as it happened before the unbundling process"
Wissner (2011b:2511)	"Crosslinking of all wind plants with real-time analysis of data and forwarding to the responsible actors"
World Economic Forum, (2010:13)	"Dynamic pricing and demand response, which are useful tools for managing load profiles and decreasing overall energy consumption"
Yu et al. (2012:1324)	"Digital management, intelligent decision making and interactive transactions of electricity generation, transmission, deployment, usage and storage"
ZVEI (2012:8–9)	"Variable electricity tariffs […], intelligent feed in management […], […] building automation […], virtual power plants"
No clear definition	
Verbong et al. (2013:120)	"It is unclear what 'smart grids' exactly constitute, how they should be implemented, and what their effect will be on the reliability and costs of the electricity system"
Yu et al., (2012:1324)	"The definition of a smart grid varies. In fact, smart grids are not only a kind of technology, but also a series of new technical and institutional innovations that can make the power grid more efficient, cleaner and smarter"

Research Institute, 2014; International Energy Agency, 2011:6). A feature of the above mentioned approaches is that they are not comparable and are rather static. Nor do they take into account that SG characteristics are not yet certain and can vary in different energy systems and different legal settings. Hence, those definitions do not provide an adequate content validity (Haynes et al., 1995:238; Lennon, 1956:295; Polit and Beck, 2006:490) of the subject of investigation. Our dynamic definition framework extends existing definitions in that it describes the unique features and interlocked characteristics of a smart grid. It also acknowledges the uncertain characteristics of a SG because of the yet unknown degree of centrality of a future energy system.

4.2. Barriers to smart grid technology implementation

In Section 3.2, we presented a list of barriers based on expert interviews. According to the grounded theory approach, barriers were labelled and inductively categorised into the categories (1) *cost and benefit*, (2) *knowledge*, and (3) *institutional mechanisms*. We also related barriers to the stakeholders identified in our literature research (Table 3). An inductive approach was considered suitable because innovation barriers are context specific (Arvanitis and M'henni, 2010:237; Blindenbach-Driessen and van den Ende, 2006:545; Fagerberg et al., 2012:1177–1178; Wu, 2012:489–490). Some barriers can be allocated to more than one barrier category; for example, *Incentive regulation hinders innovation* could be allocated to *Cost and benefit* and at the same time to *Institutional mechanisms*. In these cases, we allocated the respective barrier to the category in which the barrier has its immediate disruptive effect. For example, the barrier *Incentive regulation hinders innovation* is caused by the traditional focus on cost efficiency and the slow adaptation of the regulatory framework, i.e. an institutional mechanism. However, the disruptive effect is that the incentive regulation does not sufficiently reward investments in new technologies. Hence, this barrier was allocated to the category *Cost and benefit*.

Some of the barriers mentioned by experts have already been discussed in existing barrier literature. Most frequently discussed barriers to SG technology implementation include (1) *no business case* is perceived by end users (Curtius et al., 2012:65; Faruqui et al., 2010:6226; Fischer, 2009:16; forsa, 2010:8–24; Mah et al., 2012a:206–211; Römer et al., 2012:491; Wissner, 2011a:2514 , 2011b:2516; World Economic Forum, 2010:22; ZVEI, 2012:9–13), (2) concerns regarding *data privacy and security* (forsa, 2010:24; Kursawe et al., 2011:176; McDaniel and McLaughlin, 2009:77; Molina-Markham et al., 2012:240; Verbong et al., 2013:122; Weil, 2011:7), (3) *complexity of SG technologies* (Acharjee, 2013:201; Deblasio, 2010:17; Fischer, 2009:16; Molina-Markham et al., 2012:240; Wissner, 2011b:2516; World Economic Forum, 2010:24–25; Yu et al., 2012:1332), and (4) a *lack of planning security* (McDaniel and McLaughlin, 2009:77; Wissner, 2011a:18; World Economic Forum, 2010:9; Yu et al., 2012:1330–1331). However, our analysis revealed several barriers that have not been discussed yet. In Table 3, "+" indicates that a barrier has been discussed thoroughly, "**o**" indicates that a barrier has been discussed to a limited extent, and "–" indicates that a barrier has been discussed poorly. For example, an important barrier that has been neglected so far is the slow adaption of organisations to their changing environment.

A further addition to existing literature is the abstraction of barriers and barrier categories to identify patterns, i.e. the fourth procedural step in theory building. In our analysis, we identified three structural patterns of barriers to the implementation of SG technology. First, there is a *bidirectional interaction between organisations and their competitive environment*. For example, the incentive regulation influences the perceived business case of DGOs. In turn,

Table 3
Overview of stakeholders and barrier categories.

	Cost and benefit	Knowledge	Institutional mechanisms
Policy-makers	Incentive regulations hinder innovation (+) Regulations allow no planning security (+)	Highly complex information regarding the energy system (**o**)	Slow adaptation to the new situation (−) Principal-agent problem (−)
Smart grid technology providers	No perceived business case for smart grid technology development (−)	Uncertainty regarding the development of the energy system (−) High complexity of smart grid technologies (+) Uncertainty about data security standards (−)	Poor adaptation of the organisational structure (−)
Grid operators	No perceived business case for smart grid technology deployment (+)	Missing experience with smart grid technologies (−)	Poor adaptation of the organisational structure (**o**) No energy information infrastructure exists (+) Principal-agent problem (+)
End users	No perceived business case for smart market applications (+)	n/a	Reduced comfort (+) Perceived threat of data privacy and security (+)

if a DGO successfully launched a smart grid product for end users, other DGOs would be likely to follow. This development could change the competitive environment by the creation of a self-enforcing effect. Second, barriers in the knowledge category and uncertainty about regulations imply that stakeholders in the energy transportation industry act in an *uncertain environment*. For example, the limited capacity of organisations to process the vast amount of information on SG technologies does not allow decision making on a complete knowledge basis. Third, barriers related to poor and slow adaption indicate that the stakeholders in the energy industry have not yet adapted to the new requirements of the energy system. This fact is caused either by a slow reaction to external change or the perception that no adaption is necessary. Hence, organisations experience *institutional inertia*.

4.3. Recommendations

The recommendations presented in this chapter are a first set of options that are presented to ignite further debates and should not be considered as a fully developed master plan. They are rather abstract as they depict an accumulated set of recommendations from various experts. For this reason, some recommendations can help to overcome various barriers. As a result, we did not derive recommendation categories but provided an overview of which recommendation can help to overcome which barriers (Fig. 2). For example, the recommendation *Accept a diversity of solutions* can help to overcome the barrier *Incentive regulation hinders innovation* (Cost and benefit/Policy-makers) in that not only the currently most cost effective technology solution should be supported, but also new technology options that can become important in the future. Similarly, this recommendation can help to overcome the barrier *Uncertainty regarding the development of the energy system* (Knowledge/SG technology providers).

4.4. Alignment with existing theories

Case-specific findings are suggested to be assessed in the light of present theory (Eisenhardt, 1989:545–546). Hence, we sought a theoretical framework that can adequately explain the structural barrier patterns derived in Section 4.2. Theories with a focus on the adaption and change of organisations were evaluated. These theories are most promising because the energy sector has been a steady industry for several decades and now is being asked to fundamentally change. We draw upon adaption and selection theories presented by Lewin et al. (2004). In the case of barriers to SG technology implementation, organisations and the competitive environment are strongly interlinked. Hence, we focus on theories that link these two levels. Lewin et al. (2004:109) call them mesolevel or boundary theories. Mesolevel theories are (1) contingency approach, (2) evolutionary economics, (3) industrial organisation economics, (4) resource dependence theory, and (5) transaction cost economics (Table 4). These are evaluated according to their ability to explain the patterns derived in Section 4.2, i.e. (1) a bilateral influence of organisations and their competitive environment, (2) uncertainty, and (3) inertia.

In Table 5, "+" indicates that a theory explicitly includes a pattern, "**o**" indicates that a theory neither specifically includes nor excludes a pattern, and "–" indicates that a theory excludes a pattern. The table also includes the sources that were the basis for our assessment. It can be concluded that evolutionary economics best explains the three barrier patterns we identified in Section 4.2.

We abstracted our case-specific findings via several procedural steps towards the identification of a theoretical framework that explains barriers to SG technology implementation. We conclude that evolutionary economics provides an explanatory framework for the key findings from our analysis, i.e. the identified structural barrier patterns. First, this outcome can be valuable when designing theory-guided surveys for a quantitative analysis of barriers. Second, this theoretical framework can help to generalise our case-specific findings in order to apply them to other aspects of energy system transformations.

5. Conclusions and policy implications

SGs are necessary to cope with future challenges of our energy supply. In this paper, we inquired as to which barriers exist for the implementation of SG technologies. Furthermore, we gathered recommendations to overcome these barriers. It is now possible to grasp the term smart grid, depending on the future energy system design. With our systematic view of barriers to SG technology implementation, we provide a comprehensive basis for the derivation of policy implications. Several barriers to SG technology implementation exist that can be categorised into barriers related to (1) *cost and benefit*, (2) *knowledge*, and (3) *institutional inertia*. Recommendations to overcome these barriers were gathered, from which the following implications for policy-makers were derived.

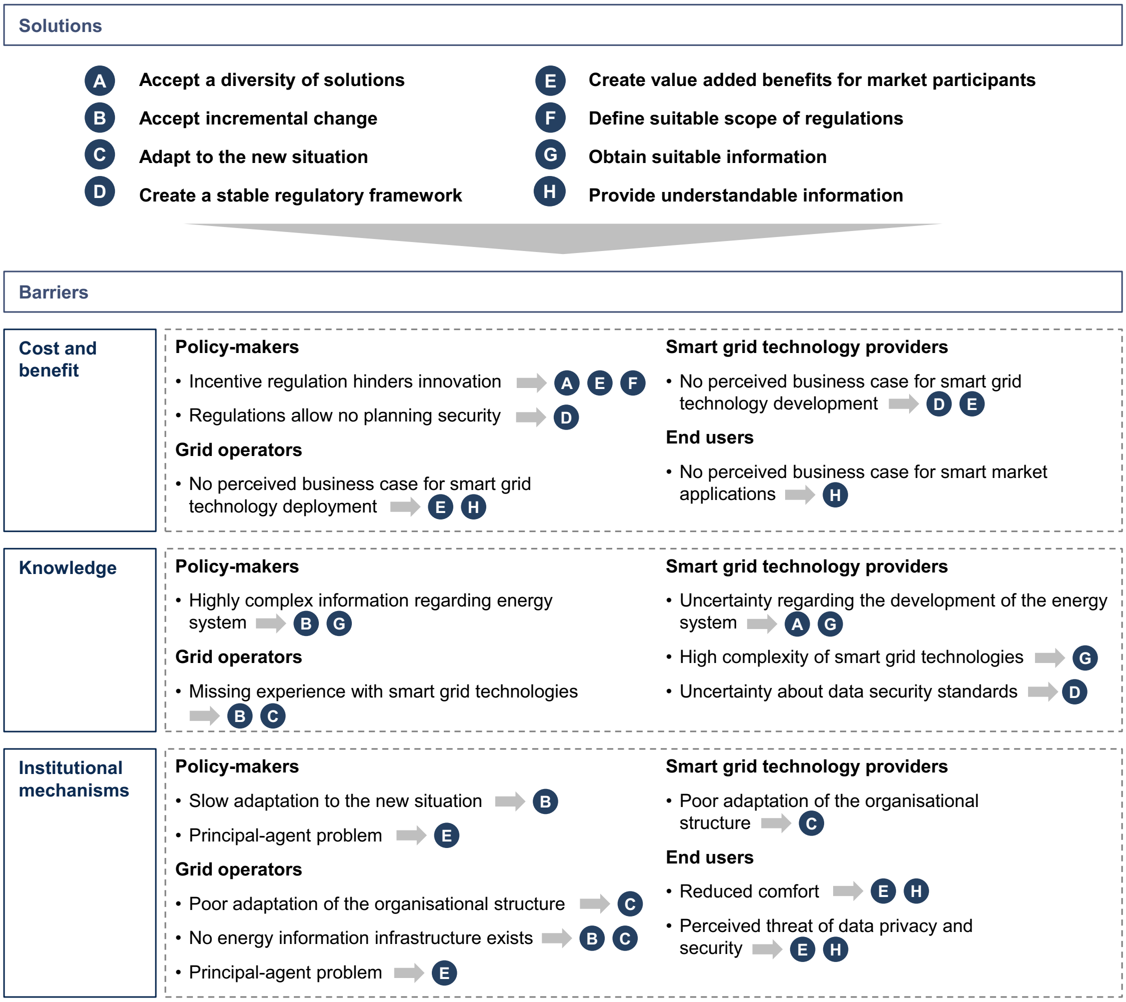

Fig. 2. Overview of recommendations.

First, a *diversity of solutions* should be accepted as a starting point. This implies incentivising a broad range of potential technology options to facilitate self-enforcing effects that accelerate SG technology implementation. This conclusion is supported by findings from Curtius et al. (2012:71–72) who argue that market acceptance is increased by a portfolio of value propositions. We suggest supporting a portfolio of solutions for DGOs. This approach would avoid new technological and regulatory lock-ins, which could hinder creative future solutions. Second, the transformation of an energy distribution system necessitates *incremental change*. This is caused by the high complexity of energy distribution systems that makes a successful master plan unlikely. Previous literature also suggests that new technology solutions should allow future upgrades (Wissner, 2011b:2517). Furthermore, a traditionally grown regulatory framework has to be amended so that it stimulates innovation capacity in addition to only cost efficiency. In greater detail, this would imply more flexibility for DGOs when it comes to charging for grid usage, for example via fees that are based on installed capacity. Similar to transmission grid operators, DGOs should be able to reclaim their research and development expenses both more comprehensively and faster, i.e. by abbreviating the regulation periods. Third, fundamental parameters of an energy system transformation should be defined and implemented into a *politically durable regulatory framework*. Römer et al. (2012:494) even argue that a regulatory framework is the most important issue for SG technology implementation. This would allow for a higher planning security of the relevant stakeholders. We suggest the implementation of a comprehensive energy regulatory framework that extends to all fields of energy policy. After the implementation of such a regulatory framework, we recommend a period of regulatory self-restraint in order to ensure a stable environment for stakeholders. An option could be a learning law that allows for small adaptions without challenging the regulatory framework in its substance. Fourth, the *interest of individual market participants should be aligned with the entire system*. Energy regulations should foster this alignment. This is particularly challenging when distributing costs and benefits between different stakeholders (Wissner, 2011a). We recommend supporting system-stabilising solutions such as demand side management or virtual power plants. Furthermore, Römer et al. (2012:494) suggested to pool property rights or to implement framework conditions that enable co-operative business models. Fifth, the appropriate *scope of energy regulations* has to be defined. It has to be decided which parts of the energy distribution system should be controlled by regulations and which parts should be run by the market. In doing so, both an appropriate level of security in innovative investments and at the same time sufficient freedom for innovations should be provided. More specifically, a clear assignment of responsibilities between the regulation authority and DGOs should be strived for when it comes to system stability. Furthermore, the scope of regulations should not only address electricity but should also provide interfaces for other energy carriers such as heat, e-mobility, and power-to-gas, which might become a part of

Table 4
Overview of adaption and change boundary theories; adapted from Lewin et al. (2004).

Theory	Central focus	Central assumptions
Contingency approach	Organisational structure-environmental contingency fit Centralisation vs. decentralisation Differentiation of organisational structures and coordination of them	Organisations can adapt structures and strategies to external requirements Changes in external requirements cause changes in organisational structure The fit of an organisational structure to external requirements affects performance
Evolutionary economics	Organisations as routines Intensity and direction of search and selection in evolution of routines Process of creative destruction Local search and incremental improvement in routines Imitation as strategy to improve routines Replication as strategy	Capabilities are embedded in routines Firms adapt and change their routines Industry structure and organisations continuously evolve Organisations are heterogeneous Organisations differ in their rates and paths of adaptation Problemistic search
Industrial organisation economics	Structure-conduct-performance Market power and concentration Intensity of industry rivalry Barriers to entry	Market structure is exogenous, determines industry performance Industry membership determines firm performance Homogeneity of firms within an industry Equilibrium-oriented
Resource dependence theory	Reduction of environmental uncertainty Interfirm relationships Power constellations and interorganisational power relationships	Negotiated/enacted environment to reduce uncertainty Organisations can affect environment within constraints Organisations have latitude for discretion Organisations pursue self-interest Asymmetric interdependence
Transaction cost economics	Structuring firm boundary Alignment of transactions and governance structures: (market, hybrid, and hierarchy) Asset specificity Transaction uncertainty Transaction costs of negotiating, monitoring, and enforcing contracts	Opportunism, self-interest seeking with guile Bounded rationality Efficient transacting as source of competitive advantage Static

Table 5
Fit of theories with empirical evidence.

	Bilateral link to competitive environment	Uncertainty	Inertia
Contingency approach	**o** Lewin et al. (2004:127)	+ Donaldson (1995:40), Souder et al. (1998:521)	**o** Donaldson (2001:168–170), Pennings (1987:224)
Evolutionary economics	+ Lewin et al. (2004:129)	+ Szulanski (1996:31)	+ Chang (1996:588)
Industrial organisation economics	– Lewin et al. (2004:121)	– Foss (1999:92)	**o** Caves and Porter (1977:241–242), Schmalensee (1988:658)
Resource dependence theory	+ Finkelstein (1997:788)	+ Hillman et al. (2009:1411)	– Kim et al. (2006:706)
Transaction cost economics	– Lewin et al. (2004:125) Roberts and Greenwood (1997:353)	+ David and Han (2004:41)	– Kim et al. (2006:706)

future energy distribution systems. Sixth, *knowledge* is a basis for policy decision-making. Policy-makers should gather information objectively and on a level of detail that allows more specific discussions. Such objective information will not obviate the strategy to incrementally change an energy distribution system, but provides a basis for better informed decisions. Also, decision makers are suggested to establish and keep a dialogue with industry associations. Benefits of SG technologies must be communicated actively to prospective end users, who may not be aware of this potential or tend to overemphasise the restrictions involved.

Experts had different views on the design of the future energy distribution system. Future quantitative research could specifically inquire into the effect of these views on the perceived disruptive potential of smart grid barriers. Furthermore, experts had opposing views on the significance of some barriers. Hence they should rather be considered as propositions. As a next step, a quantitative analysis should be performed to investigate the disruptive potential of each barrier and cross-influences between barriers. The findings of such an analysis could provide valuable insights for the development of specific recommendations to overcome the most significant barriers. Additionally, our decision to focus on Germany to avoid distortions due to different legal backgrounds can lead to other biases. For example, the necessity for SG technologies depends on the share of renewable energy in an energy system, which could lead to deviating perceptions regarding the significance of barriers. A case-specific analysis should always be undertaken prior to a transfer of our findings to other aspects of energy system transformations.

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