Energy Efficiency (2016) 9:545–562
DOI 10.1007/s12053-015-9385-8

ORIGINAL ARTICLE

Smart grid: hope or hype?

Morten Lunde · Inge Røpke · Eva Heiskanen

Received: 18 December 2014 / Accepted: 4 August 2015 / Published online: 15 August 2015
© Springer Science+Business Media Dordrecht 2015

Abstract The smart grid is an important but ambiguous element in the future transition of the European energy system. The current paper unpacks one influential national vision of the smart grid to identify what kinds of expectations guide the work of smart grid innovators and how the boundaries of the smart grid are defined. Building on data from a scenario exercise within a large Danish smart grid project, we examine how the smart grid and the conditions for its realization are defined and delimited. Our findings show that the smart grid hype embodies several implicit expectations that serve to guide research and investment and to attract new players into the field. A scenario process such as that demonstrated in this article can serve to articulate some of these implicit assumptions and help actors to navigate the ongoing transition. On the basis of our analysis, European policymakers might consider how their (intentional or unintentional) choices serve to create or maintain certain boundaries in smart grid development: for example, an exclusive focus on electricity within the broader context of a sustainable energy system. As serious investment starts being made in the smart grid, concepts like the supergrid, flexible demand and a broader *smart* energy system will start competing with each other.

Keywords Smart grid · Expectations · Scenario analysis · Flexible demand

M. Lunde
Danish Technological Institute, Copenhagen, Denmark
e-mail: molu@teknologisk.dk

I. Røpke
Aalborg University Copenhagen, Copenhagen, Denmark
e-mail: ir@plan.aau.dk

E. Heiskanen (✉)
National Consumer Research Centre, Helsinki, Finland
e-mail: eva.heiskanen@ncrc.fi

E. Heiskanen
e-mail: eva.heiskanen@iiiee.lu.se

Introduction

The European electricity system is faced with a fundamental transition. Several changes are deemed necessary in electricity markets and systems, such as improved energy efficiency, reduced carbon dioxide emissions and increased integration of renewable energy sources. In order to achieve these changes, great expectations are set on the development of a *smart grid* (e.g. Erlinghagen and Markard 2012; Verbong et al. 2013; Darby et al. 2013; Moura et al. 2013).

Smart grids are defined as upgraded electricity networks, which are enhanced with two-way digital communication between supplier and consumer, intelligent metering and monitoring systems (EC 2011). Such enhanced grids enable several applications to improve energy efficiency (such as monitoring and control applications) as well as to integrate larger amounts of intermittent, renewable energy sources (via electrical load shifting, load clipping and electricity storage). Smart grids are seen as a solution to several interlinked problems: ageing infrastructures, the need to decarbonize the energy system and the reduced availability of balancing power due to liberalization of the electricity market (Verbong and Geels 2010). The set of problems that the smart grid aims to solve are somewhat different in different countries; moreover, smart grids also feature prominently as solutions to problems of a common European electricity market (EC 2011).

While certain elements of a smart grid are already in place in Europe (Darby et al. 2013), the smart grid as a comprehensive infrastructure is still more a vision than reality. This vision is ambiguous and could entail very different technological and institutional setups (Verbong and Geels 2010; Foxon et al. 2013). The smart grid is often referred to as a *hype* (e.g. Verbong et al. 2013), i.e. a hyperbolic expectation that has as yet little concrete foundation. Hyperbolic expectations can serve to attract the interest of diverse actors (Geels and Smit 2000). Due to their ambiguity, they can also contain implicit assumptions that have serious real-word consequences: innovators may take for granted certain future conditions or mechanisms that are not self-evident on closer analysis (Truffer et al. 2008). Assumptions can also concern boundaries—who or what is included and who or what is excluded (Jørgensen 2012)—since the boundaries of energy systems are not self-evident (Jonsson et al. 2011; Martiskainen and Coburn 2011).

The ambiguity of technological hypes serves a purpose at early stages but needs to be clarified when concrete investments are realized and competing solutions need to be prioritized (Geels and Smit 2000; Alkemade and Suurs 2012). Some of the implicit expectations can be critical for the future of systemic and infrastructural innovations like the smart grid, but may require particular effort in order to be made visible. For example, Verbong and Geels (2010) identified three alternative pathways for the electricity system, each of which involves some elements from the smart grid discourse, but which imply different hierarchies in policy goals and strategies. Some scenarios maintain the status quo of incumbent actors, others would extend the scale of operation to a European Supergrid, while yet others would decentralize the energy system and prioritize local actors. Verbong and Geels (2010) have shown that smart grid scenarios and pathways have significant implications for the CO_2 reductions to be attained via smart grid investments, as well as for which actors gain power and profits in the new system configurations.

There are already several published smart grid scenario analyses from different countries (Du et al. 2009) and on a European scale (Verbong and Geels 2010; Darby et al. 2013). The ongoing transformation of the electricity system is characterized by so many uncertainties, and the whole field is so fluid and dynamic that the large number of different players needs some guidance based on organized reflection on potential developments. This need has motivated various roadmap projects (e.g. EurElectric 2010; Honebein et al. 2011; DECC and Ofgem 2014) and scenario projects related to the smart grid such as the European scenarios developed by Darby et al. (2013) and the more recent project on the development of smart grids in the UK (Balta-Ozkan et al. 2014).

Scenario exercises have sometimes been criticized for underplaying the contingency and path dependence of technological system change (Foxon 2013; Foxon et al. 2013). Yet scenario analysis can also be used to make expectations, assumptions, system boundaries and contingencies visible (Truffer et al. 2008). These are relevant questions from a policy perspective since some of the expectations underlying smart grid scenarios can be strategic (i.e. political and serving particular interests) and some may be implicit (i.e. the actors are not fully aware of their underlying assumptions). Even though policymakers often make the final decisions on support for particular technological solutions, boundaries and definitions are often made within R&D platforms involving technologists and investors (Alkemade and Suurs 2012).

In this paper, we conduct a case study of a scenario development exercise in a particular Danish smart grid R&D platform called iPower. The Danish case is relevant internationally, since Denmark invests heavily (at least three times as much as any other European country) in smart grid research, innovation and demonstration projects (Joint Research Centre 2014), due to the large share of wind power in the electricity system. Our analysis has implications for other countries (especially those that are at earlier stages in smart grid development and deployment, see JRC 2014), as it illustrates how national R&D projects can influence the future pathway of smart grid investment by including or excluding particular options. Following Jørgensen (2012), we pay particular attention to definitions and boundaries. These can be partly strategic, when actors purposefully aim to reinforce their own position, but they can also be implicit and shaped by the competencies and commitments of the actors involved. A scenario process in which the R&D platform examines its own relation to external conditions, i.e. challengers and enablers of its smart grid project, can help to surface some of the implicit assumptions and commitments that actors are not completely aware of. In this way, it helps to make visible the particular *version* of the smart grid that this platform is creating.

Our research question is: What are the explicit and implicit assumptions underlying the smart grid development work and how are the boundaries of the smart grid system drawn? To what extent can a scenario exercise serve to uncover these assumptions? Our research material draws on a scenario development exercise conducted within the iPower smart grid platform, as well as a close analysis of the interview and group discussion transcripts used to develop those scenarios. As comparative data, we analyse other alternative visions for the Danish energy system. We have used policy documents to contextualize our case, i.e. to examine what has happened before and after the scenario exercise that is our focus of analysis. It is beyond the scope of this paper to make systematic cross-country comparisons, but we include a few reflections on the differences between the issues that emerge in the British and Danish projects, respectively.

The second section presents the context of the study and the methods used to produce and analyse the data. The third section presents the results of the scenario development process and compares them with other visions of the future Danish energy system. The fourth section discusses the results and their limitations, and the fifth section presents our conclusions and implications for policymakers developing smart grids and sustainable energy systems in other national or international contexts.

Methods

We conduct a two-layered case study analysis of the Danish smart grid research and innovation project iPower. The primary data for this study consists of participant observation of—and material from—a process to develop strategic scenarios, conducted in the Danish smart grid research and innovation project iPower. The first author of this paper facilitated the process, while the other two authors participated in analysing the results and the recorded and transcribed interview material on which the scenario framework is based, as well as in comparing the scenario results to visions created by other researchers. We then analysed these data for implicit and explicit assumptions (Truffer et al. 2008), with a particular focus on how system boundaries are defined. Since expectations do not operate in institutional vacuums, we started by making a close analysis of the institutional context and immediate history leading up to the establishment of the iPower platform.

Context of the study: the smart grid in Denmark

We analyse smart grid scenarios in the context of the ongoing transition of the Danish energy system. With current political targets aiming for an energy supply based on 100 % renewable energy sources by 2050 and 100 % renewable energy supplying electricity and heat already by 2035 (Danish Ministry of Climate, Energy and Building 2011), both the supply and demand sides must undergo radical changes. On the supply side, wind power is emphasized as the main source of electricity, with the partial aim of 50 % wind power in the electricity supply by 2020. Coal-fired power plants are to be phased out by 2030. On the demand side, especially oil-fired burners are expected to be phased out by 2030 (Danish Ministry of Climate, Energy and Building 2011).

The promotion of an intelligent electricity grid had a real take-off in Denmark in 2010 when both the report of the Danish Climate Commission (Klimakommissionen 2010) and a specific report on smart grids were published (DEA and Energinet.dk 2010). The task of the Commission was to outline how Denmark could become independent of fossil fuels by 2050 and meet the target of reducing greenhouse gas emissions by 80 to 95 % compared with 1990—simultaneously with continued economic growth and increased transportation. The main elements of the plan are energy savings (particularly related to housing); a considerable increase in the use of wind energy for the provision of electricity, also to be applied for heating and transportation; and the use of biomass as the most important system backup. In relation to the electricity system, the Commission first states that fluctuating wind production calls for both stronger transmission grid connections to other countries to export surplus electricity and to import when production is low, and for the development of energy storage. But this is immediately followed by a call for a more intelligent electricity system where also consumption becomes flexible. The argument is that flexible consumption will reduce the costs for investments in grids and production capacity. The Commission suggests that the government should cooperate with the transmission system operator (TSO) and the distribution service operators (DSOs) to draw up a plan for the development of an intelligent energy system.

Also in 2010, the TSO and the Danish Energy Association published the report *Smart Grid in Denmark* (DEA and Energinet.dk 2010) popularizing the smart grid concept as a shorter and more trenchant synonym for the intelligent electricity system and elaborating the vision. The focus of the vision is flexible electricity consumption in households. With the increasing amounts of wind-based electricity consumption, it will be expedient for households to use more electricity for heating and transport instead of fossil fuels. This implies an increasing number of heat pumps and electric vehicles, and in combination with an expected increase in household energy production (solar panels, etc.), this will put considerable pressure on the distribution grids. This challenge can be met either through reinforcement of the distribution grids or through the establishment of a smart grid enabling flexible management of consumption. It is repeatedly emphasized that this can be done without any loss of comfort for consumers.

The argument for the smart grid is that this is the cheapest and most effective way to upgrade the electricity system: a traditional extension is estimated to cost 7.7 billion Danish kroner (DKK) in investments, while a smart grid strategy is estimated to be more expensive (investments costs of 9.8 billion DKK), but simultaneously to involve social benefits amounting to 8.2 billion DKK. These benefits are derived from savings on regulating power and reserves (2.4), savings on electricity production (4.4) and reduced costs related to the promotion of energy savings (1.4). The idea is that the benefits can be realized through commercialization so that all actors get economic incentives to participate in the transformation (p. 17). It is noticeable that the vision concentrates on distribution grids and household flexibility. Only a small note (p. 11) mentions that the TSO has already concluded that a smart grid is no alternative to extensions of the transmission grid.

The DSO perspective in the report is also evident in one of the two requests to policymakers, namely the need for regulatory changes to admit DSOs to make smart grid investments without running economic risk. The other request is government support for development and demonstration activities—a request that turned out to be quite successful, as already mentioned. The need for regulatory changes of the electricity sector was later explored by a committee established in 2012, focusing on three goals: green transformation, cost efficiency and competition and consumer protection. The committee published its report in 2014 (Udvalg for elreguleringseftersynet 2014), including suggestions intended to improve the incentives for the DSOs to invest and to give them more scope to decide whether they want to invest in grid reinforcement or smart grids. The Danish Energy Association took part in the committee work and generally agreed in the report, but nevertheless provided a note of dissent regarding several of the recommendations. It is not yet possible to assess how the regulation will be changed.

The Danish TSO and the Danish Energy Association later elaborated and popularized their vision, as can be seen, for instance, in a video (Energinet.dk 2013; DEA and Energinet.dk 2012). Here, it is clear how supergrid elements are combined with the national smart grid development. The elements include large wind turbines at sea; strong international grid connections; large flexible power plants based on biomass; large-scale storage, e.g. related to heat pumps in district heating; the use of electric vehicles; and local energy production based on small heat pumps, solar panels and micro CHP. Still, the vision tends to focus mainly on the transformation of the electricity grid: although there are links to the systems related to heating and transport, the interplay between the systems is not elaborated. As we will return to in the discussion, this perspective is also challenged, but the dominant vision that forms the basis for Danish smart grid activities is this combination of supergrid and smart grid focusing on the DSO perspective.

These political targets and smart grid visions have given rise to expectations of (1) challenges at the transmission system level of balancing electricity production and demand as a consequence of increased fluctuations in the energy supply and (2) congestion management and voltage control problems in the distribution grids as a consequence of increased electrification and decentralized photovoltaic electricity production. These expectations appear to be the main driver behind an ambitious research effort within the smart grid, which is seen as a part of the solution to these problems by facilitating intelligent control of decentralized power consumption in both the industrial and domestic sectors (DEA and Energinet.dk 2010).

The iPower project as a case study

Our analysis focuses on the iPower project, which is one of several Danish smart grid projects. It was launched as a strategic platform for research and innovation with the purpose of developing intelligent control of decentralized power consumption and reducing investor uncertainty regarding smart grid and flexible consumption solutions. The project runs from 2011 to 2016 and is developing smart grid technologies for the electrical grid, industries and residential applications. With 30+ participating organizations from universities and industry, involving more than 190 people, the partners represent a wide range of stakeholders, including the following (see iPower 2014 for the full list):

- DSOs, balance responsible parties and electricity traders, e.g. DONG Energy and NEAS Energy
- Interest organizations, e.g. Danish Energy Association
- Companies developing software and hardware for home energy management and intelligent monitoring and control of distributed energy resources, e.g. Greenwave Systems, Develco Products, Kamstrup, Lodam Electronics, Neogrid Technologies, Insero Software and IBM Denmark
- Companies developing and supplying products that could become distributed energy resources in domestic homes, e.g. Metro Therm (water heaters and tanks) and Nilan (heat pumps)
- Companies developing and supplying industrial products that could become or enable industrial distributed energy resources, especially cooling facilities, e.g. Danfoss and Grundfos
- Engineering consultancy companies, e.g. COWI
- Danish and foreign research institutions, e.g. University of California, Berkeley (USA), National Consumer Research Centre (Finland), Aalborg University, Technical University of Denmark, Kolding School of Design and Danish Technological Institute

As the reader may notice, the stakeholders in the project primarily have an interest in a smart electricity system, while the stakeholders do not include actors with for instance a gas distribution system focus or even the Danish TSO, Energinet.dk, having the overall balance responsibility for both the electricity and the gas grid. Both the project stakeholders and the original project application have focused on a smart electricity system rather than a smart energy system. With this smart electricity grid focus, the project has been divided into seven work packages with each their own subfocus (iPower 2014):

1. Domestic demand response
2. Industrial demand response
3. Distribution grid operation
4. Control and market operation
5. Socio-economic and investor evaluation
6. Consumer behaviour
7. Information sharing platform

During 2012, a working group consisting of select steering committee members and work package leaders revised the vision and strategy of the project. Among several consequences of this revision was a decision in early 2013 in the work package leader group to initiate a process of developing strategic level scenarios.

Scenario development process

A scenario team consisting of several iPower partners formulated the purpose, objective and main research question of the strategic scenario process. The purpose was twofold: (1) to provide a helicopter-perspective expert-based strategic communication tool and (2) to develop a framework for the following quantitative scenarios for socio-economic and investor evaluation. With this purpose, the scenario team decided that the scenario exercise should not focus too much on what kind of smart grid may be realized in Denmark. Rather, the focus should be the conditions for realizing a particular vision or version of the smart grid. The objective of the strategic scenarios became: "To identify the key determining factors for the future adoption of smart grid in Denmark and develop a framework for 2–4 strategic level scenarios with a time horizon of 2025 (iPower 2013a, p. 5)".

The methodological approach applied was based on an analytical, explorative and deductive scenario development method aiming at developing probable futures for a problem with a relatively high uncertainty and long-term time horizon. This approach was originally developed by Rand Corporation in the 1950s and 1960s and applied in modified versions by e.g. General Electric, Shell and Global Business Network (Andersen and Jørgensen 2001). In brief, the method consists of the following steps (Andersen and Jørgensen 2001; Heijden 1998): (1) identify key determining factors for the problem investigated (this includes structural conditions, major trends and key events); (2) assess each key determining factor for (a) significance for the problem investigated and (b) predictability; (3) link and group the key determining factors into axes of significance for the research question; and (4) provide intuitive estimates of possible futures based on the axes.

The methodological approach was modified for the iPower project setting, characterized by a large project consortium with 35+ participating institutions; an ambition to include all partners in the scenario process; and limited resources to conduct the process (as it was not a part of the original project plan). One of the partners, the Danish Technological Institute, undertook the assignment of facilitating the process. This was done by the following activities, all completed in 2013:

- Feb–May: Trend research, development of interview questionnaire and preliminary expert interviews.
- May: Focus group interviews with all work packages at a project consortium meeting. The focus groups all consisted of interviewees from the same work package interviewed from the same open-ended questionnaire for 1 h.
- June–Aug: Information processing and internal reporting of identified key determining factors.
- Sep–Oct: A scenario development team was constituted by a select team of nine iPower participants, who prepared and conducted a scenario framework development workshop. The workshop participants agreed upon a draft of the two chosen axes, including the encompassed factors in each axis.
- Nov: Presentation of results at the iPower consortium meeting and incorporation of comments into the final deliveries: an internal report and a public flyer (iPower 2013a, b, respectively).

This process enabled the initial scenario development questions to be answered by approximately 80 participants in the iPower platform.

Analysis

The interview material, documents and the inputs and outputs of the scenario process were analysed using qualitative classification. All documents and interview transcripts were reviewed with a focus on similarities and differences in (1) definitions of the smart grid; (2) interpretations of drivers, supporters, competitors, delayers and barriers to smart grid adoption; and (3) understandings of which technologies, actors and institutions are considered as being within and which are considered as being outside the smart grid vision. Finally, the definitions and boundaries developed within the iPower platform were compared and contrasted with other influential visions of the future Danish energy system, identified with a literature search.

Results

Several insights were obtained throughout the iPower interviews, of which selected results are presented in this section. To frame the presented insights, one important perspective is that among the participants of the iPower platform, there was no clear, unanimous definition of smart grid. When prompted by the initial question *what is your definition of smart grid?*, the members of one work package answer they use the definition provided by the European Smart Grid Platform. Discussions in other work packages circled around *an integration of production and demand of electricity*. This illustrates the complexity of the Danish smart grid vision, which is more complex than e.g. existing demand response programmes in the USA, where event-based peak load reductions from large-scale consumption units occur only a few times a year (Harbo et al. 2013). The Danish vision is more extensive, including aggregation and trading of flexibility from large to small consumption units on the electricity markets in a more continuous manner.

Based on analysis of the interview material, the scenario team identified the following types of key determining factors for the adoption of smart grid in Denmark (iPower 2013a, b):

- Drivers, which themselves may drive the adoption of smart grid in Denmark.
- Supporters, which may support primary drivers to ease or accelerate the adoption of smart grid.

- Competitors, which may deteriorate the smart grid business case.
- Delayers, which may slow the adoption of smart grid.
- Barriers to smart grid adoption were not found, as the analysis labelled them as either competitors or delayers.

In the following section, key factors are described based on the data material from iPower (2013a, b). The reader may notice counterarguments exist in different sections, which in most cases are due to the categorization into the above factors.

Drivers

Across all the interviewees, there was broad consensus that two primary factors are driving the smart grid development in Denmark: (1) increased integration of renewables in the energy supply and (2) expectations of business possibilities leading to growth for Danish companies. The first driver originates in the political ambitions for a transition to an energy system supplied entirely by renewable energy sources. The iPower participants perceive the underlying motivation for these ambitions to be a combination of a transition to a low-carbon society and independence of fossil fuels imported from politically unstable regions or powerful associations with influence to monopolize the markets. The challenge in creating this driver is that the increasing amount of renewables (primarily centralized wind power) supplying the electricity grid will result in a highly fluctuating electricity production, introducing new needs for services to balance production and consumption. At the same time, increased electricity consumption of an electrified transport sector and domestic heat pumps combined with decentralized photovoltaic electricity production will challenge the voltage control and introduce congestion management problems in the distribution grids.

> It is the desire to reduce CO_2-emissions and to become independent of the OPEC-nations and oil, that makes us go for renewable energy, […] this drives us into wind turbine based electricity production […]. The socio-economic best thing to do with the electricity produced by wind is to consume it ourselves, rather than sell it to Germany and other places. Then we have to invent these devices to use the electricity. Electric vehicles and heat pumps changes [consumption] from a petrochemical sector to an electricity sector, they need the electricity produced by the wind turbines […]. Here comes the problem: All these new consumption devices create some [consumption] fluctuations we can't deal with, and they create some expensive grids, where we have to make investments. […] We simply need the customers as partners in the future, to consume the energy when it is produced.—WP6 participant

The second driver regarding business potential for Danish companies appears to represent two viewpoints: (1) that we must invest heavily in smart grid development and demonstration in Denmark to establish an exemplary home market as a basis for export and (2) that the participating companies in iPower already see business potentials or perhaps even already export smart grid technologies to other markets with weaker grids than Denmark and therefore represent a better business case for technologies for intelligent control of decentralized power consumption. This driver appears to be the main driver behind industry investments so far, but it does not in itself improve the business case for a market of flexibility services in Denmark.

Supporters

Several supporters for smart grid development were identified. These represent technologies, tendencies, motivational factors, etc. that provide opportunities to ease the introduction and adoption of flexible consumption and smart grid technologies. The supporters cannot themselves drive smart grid adoption in Denmark but may provide varying opportunities to support the adoption. They range from energy efficiency initiatives over increased ICT penetration to increase in comfort and other non-monetary value creation opportunities.

Energy efficiency is considered a supporter by the iPower participants, as it may provide a beachhead for introducing smart grid technologies and flexible consumption. Energy efficiency initiatives and technologies are known and to a certain extent requested among both industrial and domestic consumers. By offering a combined programme of energy efficiency initiatives and flexible consumption solutions, more consumers may buy into flexible consumption. Especially for the private consumer, for whom it is difficult and/or irrelevant to distinguish between savings from lower energy consumption or consuming at the right times, a bundling of energy efficiency and flexible consumption is expected to make sense, especially if it does not lead to loss of comfort.

> I think there are energy efficiency possibilities compared to how a heat pump is operated today. It may be a good business for people to get some surveillance [on the performance of the heat pump] set up, and then there's sort of established a beachhead to start [external] control, because the signal back and forth is already established. At first, the owner gets an opportunity for optimizing the heat pump, which holds some value in its own.—WP6 participant

The increased penetration of information and communication technologies (ICTs) was also considered as an important supporter for the adoption of smart grid. By relying on existing and already adopted platforms in both industry and domestic homes, ICTs were expected to drive down development costs and reduce the need for investments. Furthermore, utilizing well-known platforms was expected to ease the introduction of technologies to facilitate and manage flexible consumption.

> Key players – telecom companies, TDC, Telenor – are entering this field right now. From TDC [Danish telecom provider, offering entertainment services via the telecom subscription] you can buy a package with burglar alarm, also containing an app for smartphone, where you can turn plugs on and off. They also have a gateway. It's very easy to build upon such a system. For instance demand response.—WP1 participant

An open platform for new services was brought up as a supporter—or almost as a prerequisite—by several interviewees. Apart from containing the standards for communication protocols, etc. to prevent proprietary solutions developed in silos from dominating the market, the platform was described as a means for lowering entrance to the smart grid market by allowing technology-developing companies, fleet operators, aggregators and the like to develop competing solutions for the same platform. Several interviewees described it as *the app store for smart grid solutions* with references to both Apple's App Store and the American Green Button initiative,[1] which enables electricity customers to securely download their own energy usage information from their utility and apply it to a range of web and smartphone tools to make more informed energy choices and procure tailored services.

> It is very important to have an open platform for communication. It is important to have new services to customers – and it is closely related to having standardization: an open architecture.—WP2 participant

The iPower participants brought up various non-monetary value creation opportunities as means for improving the smart grid business case(s) and thereby supporting adoption. These opportunities are closely related to the green transition driver, although more conventional business ideas of comfort and convenience, related to the ambiguous smart home concept, also appeared.

Regarding the industrial consumers, non-monetary value was expected to derive mainly by catering to corporate social responsibility initiatives, for instance by reducing electricity consumption at times when CO_2 emissions from the electricity mix is high.

> For us there is also value in regards to the whole CO_2 footprint area that we work with. So technology that can reduce that is important. At the moment you cannot reduce the CO_2 footprint by buying electricity from a windmill for example. It is only in that way you manage your energy.—WP2 participant

For the domestic consumers, some of the non-monetary value creation opportunities identified ranged from offering smart grid solutions in combination with convenience products to offering the consumer a way to *do the right thing* for the environment as well as society, either as an individual or collective effort. These value propositions may be amplified by co-ownership of distributed energy resources and by diffusion through social media.

> It has turned out this environmental driver is pretty strong among the population. This [smart grid] could be something which creates a renewed consciousness about renewable energy and CO_2 emissions [...] Maybe we can create a popular

[1] See http://www.greenbuttondata.org/, last observed May 8, 2014

> movement to save the planet – it's big words we're using now right?—WP6 participant

Responsible behaviour might also be encouraged through gamification, thus stimulating people's playfulness and creating lasting incentives for flexible consumption.

> There's also an opportunity in the penetration of handheld devices and mobile units, which makes boring things like energy efficiency in your own home or interacting with the grid easily accessible in some way, where it stimulates your playfulness – and people are playful. But to make it so it really works and is exciting for a longer period of time, I don't know about that.—WP6 participant

Competitors

Many iPower interviewees expressed skepticism as to whether there is a business case for the smart grid in Denmark.

> The engineering part of the smart grid gets a lot of attention, but what about the socio-economic aspects? I doubt if the economic side is even there. So the problem is whether just to install smart grid technologies and get a system that functions well or only install smart grid to the amount where the business side is still there?—WP5

The smart grid business case has been further specified as to whether flexibility services can compete with alternative solutions on the electricity markets to solve the expected balancing and congestion management problems caused by the green transition to renewable energy sources. The identified competitors therefore all offer alternatives to flexibility services on the electricity markets and risk deteriorating the business case for flexibility services. These competitors do not compete with e.g. manufacturers of heat pumps or smart home technologies often associated with smart grid, unless the business case of these technologies depends solely on selling flexibility services, which would be the case for an aggregator only trading with flexibility services. The identified competitors are related to the problems they solve for the existing actors in the electricity grid:

- The TSO can increase energy exchange capacity with neighboring countries to balance production and consumption, and exchange capacity is expected to increase. However, this path also faces limitations due to the lack of capacity in the German grid, due to shared weather conditions with Northern Germany and due to increased demand for the limited supply of hydropower and nuclear power in other countries.
- The TSO can buy ancillary services from central power plants to balance production and consumption. Presently, the capacity is expected to decrease, but political intervention may change this trend by making it profitable to ensure backup capacity or by providing it from publicly owned facilities.
- The DSOs can reinforce the distribution grids to increase capacity and avoid congestion management problems. Especially in Denmark, DSOs consider this a viable option, as the distribution grid is very well developed.
- Large-scale energy storage and smart energy technologies, enabling efficient conversion between energy forms, may be used as alternatives to flexibility services in the longer term. Although the smart energy approach now receives a lot of research attention in Denmark, the scenario team has evaluated these competitors to be of less importance in 2025, which is the selected time horizon.

Initially, the competitors were interpreted by the scenario team as barriers to the adoption of smart grid in Denmark, due to many critical statements from the iPower participants, e.g.:

> With a scenario with a lot of wind energy there should be more value also for consumers […] But the problem is the connection to Norway, which will make the value and the point of Smart Grid less worthwhile.—WP4

Subsequent discussions in the work package leader group clarified that these barriers were equally important partial solutions to the problems that smart grid may contribute to solve, wherefore the barriers were later defined as competitors to flexibility services provided by smart grid technologies.

Delayers

According to the scenario analysis, the most important factor delaying the adoption of smart grid in Denmark is that the problems that the smart grid is trying to solve have not yet emerged. Denmark has a very well-developed electricity grid with extensive connections to neighboring countries, as well as a distribution grid with ample capacity. The penetration of heat pumps and electric vehicles has not occurred as rapidly as anticipated, thus postponing the congestion management and voltage control issues in the distribution grids. Furthermore, the solar PV expansion has not challenged the distribution grid as expected. The further penetration of these technologies has proven very hard to predict, and as the penetration until now has been lower than predicted, expectations for the actual arrival of the problems—and thereby the business case for flexibility services—have significantly decreased. On the transmission system level, Denmark has recently achieved a new world record by having 57.4 % of the electricity supply covered by wind power throughout December 2013 (DR 2014), handled with the traditional balancing means of electricity trading with neighboring countries as well as ancillary services from central power plants.

> […] we don't really have the problems that we are talking about.—WP3 participant
> From the perspective of the normal Dane, we have a smart grid: when I push the button I have the light. Quite smart. Why change that?—WP1 participant

A delayer related to both the above-described lack of problems and the competitors is the challenge of establishing the roles and business cases of all the different actors in the smart grid, especially in the startup phase. Both existing and new actors are taking part in the development of the system with expectations of a (high) return on investment, but interviewees argue that there is too little value in proportion to the amount of investments needed to build a market with all its existing and new actors. Examples of these new actors include the aggregators, who aggregate the flexible consumption from smaller distributed energy resources and bid them into a market of flexibility services, demanded by the TSO, the DSOs and the balance responsible parties.

On top of this, some participants pointed out that regulation and market design is lagging behind. The rules and regulations on the electricity markets seem to favor larger and more complex technical units, with examples given such as the 10-MW minimum bid size to enter the regulation power market, which excludes bids from all but the most aggregated of the smaller units. Furthermore, the lack of variable time-of-use tariffs provides little incentive for flexible consumption, as the electricity price paid in Denmark primarily consists of tariffs.

> One of the problems is that when you look into the things you need to be able to handle – all the rules and regulations are written for big power plants. It is necessary to change the rules and regulations to match the new circumstances. And it shouldn't be the same rules for all – for big and small players.—WP2 participant

A further unresolved problem was identified that limits the possibilities for DSOs to invest in flexible consumption rather than grid reinforcements: Dynamic tariffs, varying in both time and place, will discriminate the customers by increasing the price in one geographic area with capacity problems, but not in neighboring areas without capacity problems, contrary to existing tariff rules.

Lack of standardization frameworks and communication standards were also brought up as something that may delay the adoption of smart grid. With examples given such as the IEC 68 150 aiming at substations, standards seem to favor larger and complex units, as the technical implementation of IEC 68 150 is so complex that it is almost impossible in consumer products such as PV inverters and heat pumps. Standards for smaller units are under development but not yet fully ready for implementation. Proprietary solutions may circumvent this but will on the other hand impede competition and drive up costs.

> Standardization within this industry takes forever. If you compare to what is happening to internet, you know, a new standard will establish itself within a few months or half a year, maximum. Within the smart grid, it takes 5+ years to get it through the standardization organizations.—WP1 participant

Security and reliability issues were also mentioned as possible delayers. From an industry perspective, the core function, quality and planned deliveries of the electricity-consuming processes cannot be compromised by selling flexibility services, especially if the business case for selling flexibility is relatively low.

From a domestic perspective, the reliability of household chores cannot be compromised and the billing based on smart systems must be meticulously correct. From a grid perspective, the traded flexibility services must be delivered as promised, or the resulting balancing or voltage control problems may result in penalties from other actors in the grid and/or even black-outs.

> Who should pay for the imbalances in the system? Who takes on the cost? Consumers, aggregators, government or somebody else? Is it a question of who has the responsibility?—WP1 participant

In continuation to the above concerns, none of the (industrial) companies among the project partners expressed interest in developing, owning and managing the platform for new smart grid services, brought up as a supporter for smart grid (see "Supporters" section). The companies were reluctant to take the responsibility for the quality and reliability of the products and/or services launched by other actors through this platform. This dilemma of open vs. closed platforms has previously been identified by e.g. Giordano and Fulli, who claim that "platform owners might need to exert regulatory control of the platform" since "When no control is exerted, degradation of the platform may arise as a consequence of low quality services provided by undesired platform participants, cyber-security threats etc." (Giordano and Fulli 2012, p. 258).

Furthermore, the ambiguous definition of the Danish smart grid initially described at the start of this section could pose a delayer in itself. When smart grid is perceived as a relatively unclear but very extensive system solution with a multitude of actors, technologies, products and services all integrated and heavily dependent on each other, the development and adoption are exposed to a chicken and egg dilemma: Which elements of the system must be defined, developed and implemented first, and how can they be implemented on commercial terms if they depend on yet-to-come conditions? To several interviewees, it seems as if the Danish smart grid is *all or nothing*.

The scenario framework

After evaluation and linking of the key determining factors, the scenario development team developed a framework for analyzing the conditions for the future smart grid development (Fig. 1).

The horizontal axis *green transition and increased electrification* is an expression of the number of challenges that the smart grid may contribute to solve. The axis is primarily based on the integration of renewables in the electricity supply and electrification of the demand side, including the following factors: expansion of renewable wind power and solar panels, penetration of electric vehicles and heat pumps and carbon price changes (factor added at the scenario development workshop).

The vertical axis *smart grid readiness* is an expression of how conventionally or *smartly* Denmark chooses to solve those challenges: In the conventional manner, the Danish energy system may balance with electricity exchange and ancillary services from central power plants and avoid congestion management problems with reinforcements of the distribution grids. In the *smart* manner, there is a greater utilization of flexibility services from decentralized electricity consumption units to solve those challenges. Factors included in this axis are all the competitors: TSO balancing via international electricity trading and centralized power plants and DSO grid reinforcements instead of congestion management. Smart energy and large-scale energy storage are however not considered important for the time horizon of these scenarios, as storage technologies and electricity-to-gas technologies were evaluated by the scenario team as too cost-inefficient or immature to play a significant role by 2025. The following supporters are also included: integration of energy efficiency and flexible consumption; non-monetary value creation (environmental and comfort aspects); and increased penetration of ICT and open platform(s) for new services. Furthermore, the axis encompasses the following delayers: lack of *smart-grid-ready* rules and regulation, lack of open communication standards and security and privacy issues.

The original iPower vision is located in the smart green quadrant and is thus dependent on a combination of continued green transition and electrification combined with a greater utilization of flexibility services rather than conventional means for balancing and congestion management. The scenario team outlined a series of indicators for each quadrant, concerning both key events, which indicate which future the development may lead to, but also containing characteristics of each possible future:

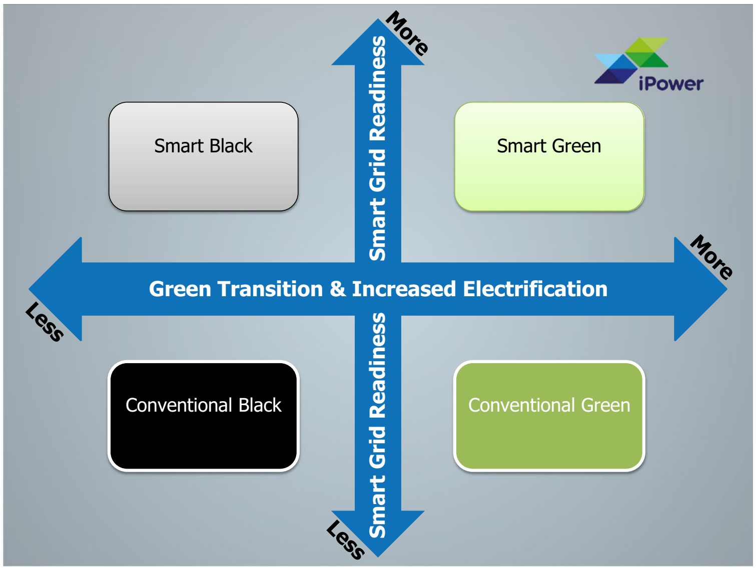

Fig. 1 A framework for analyzing the conditions for the future smart grid development

- Smart green: The smart green quadrant is characterized by underlying factors such as continued concern for the environment combined with continued high ambitions to develop and integrate smart solutions. Key events include political adoption of ambitious European 2030 targets, an international climate agreement and continued support to the current ambitious Danish climate and energy targets. To improve conditions for smart solutions for the challenges posed by enactment of these political targets, smart grid standards and variable tariffs are implemented. These initiatives enable the TSO and the DSOs to utilize flexibility services for balancing and avoiding grid reinforcements, thus developing a market where multiple aggregators trade flexibility from large and small DERs. Whenever industrial or domestic consumers invest in new electricity-consuming devices, they are *smart by default*.
- Conventional green: The conventional green quadrant is indicated by similar continued environmental concern, while the ambitions for *smartness* are lower, instead relying on conventional strategies for solving the challenges caused by the green transition. Politically, the targets for the green transition remain high, but smart grid standards and support schemes for flexible consumption favor larger, semi-decentral DERs, with few aggregators focusing on larger DERs, while industry and domestic consumers go for conventional energy efficiency rather than consuming electricity flexibly.
- Conventional black: The conventional black quadrant is characterized by a reduction in the political energy and climate targets of both the EU and Denmark, maintaining status quo for the Danish electricity grid, which easily handles fluctuations from renewable energy as well as a minor electrification of the demand side with conventional strategies. Therefore, no need for flexibility services will emerge and no political support schemes will be adopted to improve the conditions for smart DERs.
- Smart black: The smart black quadrant emerged as a rather surprising result of the process of combining the axes. Driven by export potential to other regions with other drivers for a smart grid, ambitions remain high to develop smart solutions, while reduced concern for the environment leads to a significantly reduced business potential for flexibility services in the Danish electricity grid. Smart grid standards are developed and implemented by standardization organizations (because they are needed in other regions with other smart grid drivers), while only the largest and most flexible DERs are aggregated and bid into the existing electricity markets in Denmark. The industrial consumers go for energy efficiency rather than flexible consumption, although they utilize smart technologies to achieve a higher energy

efficiency as well as greater efficiency in their work and production processes. The domestic consumers go for a smart home—not for selling flexibility services, but for energy efficiency and comfort purposes (iPower 2013a).

The relevance of the scenario axes can be further examined through a comparison with other similar scenario exercises. One such exercise, using a similar methodological approach, was conducted by the Danish TSO, Energinet.dk, which is not among the iPower partners. These scenarios took departure in the key challenge: *There is a range of factors that influence Energinet.dk's investments in the electricity and gas grid. How will these factors develop from today until 2030?* (Energinet.dk 2007, p. 10). One of the axes in this project was once again the green transition, in this case more broadly expressed as whether environmental concerns will become/remain a high or low priority. The other axis was selected to indicate whether Denmark would be internationally or non-internationally oriented. This emphasizes the importance of whether Denmark will become and/or should be self-sufficient in the supply of energy, which for instance will have large implications on the *smart grid competitor balancing via international electricity trading*, as identified in the iPower scenarios. With Energinet.dk's scenarios being developed by the Danish TSO, the emphasis on self-sufficiency reflects one of the primary options the TSO has today to balance production and consumption. The iPower platform on the other hand has the purpose of reducing investor uncertainty regarding technologies enabling intelligent control of decentralized power consumption. Taking departure in a hypothesis that smart grid, including a market of flexibility services, has a good business case, it therefore made better sense to the iPower scenario team to emphasize smart grid readiness as the other main factor to take into account.

Other research communities have worked on visions that share some of the elements (Kwon and Østergaard 2012) but also suggest different paths for the development of the energy system, where the interplay between systems is more in focus. Increasingly, these visions are referred to as smart energy rather than smart grid (e.g. Lund et al. 2012). A key rationale of these visions is that it is better to use Danish wind energy at home instead of engaging in large-scale trading in electricity. The trading is not so beneficial, because the price of electricity is low when it is windy, so the large investments in international connections are better used for developing smart energy systems that can increase the value of wind-based electricity. This requires more attention to the integration with the use of the gas grid, the use of large heat pumps in district heating, more uses of electricity in the transport sector and considerably more focus on energy savings. There is also more focus on the need for mobilizing public support, for instance, through co-ownership of wind farms. Households need to be more actively engaged. In addition, questions regarding ownership are critically examined: backup capacity could be organized as public ownership. This alternative *green* vision, which is not conventional but not purely based on flexible demand, is not explicitly included in the iPower scenario framework.

Implicit expectations revealed by the iPower scenario exercise

The scenario process identified key drivers and supporters of the smart grid development. It also served to show how further development is conditional on the continuation of these drivers and supporters. These include the continued increase in the penetration of intermittent renewable energy sources and the global business potential for smart grid solutions (which however depends on the emergence of relevant references from the domestic market, which in turn is slow to develop). Energy efficiency was identified as an important beachhead for a flexibility market, and continued ICT penetration, open ICT platforms and voluntary *green* initiatives by companies and citizens were identified as key supporters.

The scenario process also highlighted several competitors, which could jeopardize a business case for flexibility services, such as the supergrid, conventional centralized ancillary services, reinforcement of the distribution grid and potential developments in electricity storage or conversion to other energy sources. The identification of the conditionality of the smart grid on certain supporters also helped to articulate delayers of the smart grid development, including a slower-than-expected diffusion of end-use equipment demanding or facilitating increased flexibility. The relatively small financial value inherent in the flexibility market was also identified as a delayer. Additionally, several barriers in the regulatory system and existing standards, which favor large-scale solutions, were identified as delayers.

Table 1 shows our analysis of the explicit and implicit inclusions and exclusions concerning the scope of the research, development and demonstration conducted in the iPower platform. *Explicit* (row 2) refers to boundaries and distinctions that were articulated from the start, e.g. in the iPower White Paper, whereas *implicit* (row 3) refers to boundaries and distinctions that were not articulated. Implicitly, the iPower platform built on assumptions concerning a business case, the future need for flexibility and the existence of an export market in countries with less stable distribution grids. Yet these were shown to involve some assumptions that turned up to be problematic. The most important of these was the assumption that a societal business case can be turned into a business case for private investors—in particular, if the market for flexibility is limited and there are several solutions competing for a limited market. Another is the time dependence of the smart grid: flexibility was expected to become necessary in the future, but not yet—and perhaps not even in the future if competing solutions arise. A third was the need for domestic references in order to convince export markets, where there might be a stronger demand for smart grid technologies than in Denmark.

Table 1 Explicit and implicit inclusions and exclusions in the scope of the iPower platform revealed by the scenario process and comparison with other visions for the future energy system

	Inclusions (issues perceived of as within the scope of the smart grid)	Exclusion (issues perceived of as outside the scope of the smart grid)
Explicit	Drivers: increased penetration of renewables, global business potential for smart grid solutions Supporters: energy efficiency, continued ICT penetration, open ICT standards, voluntary "green" initiatives by citizens and companies	International trade in electricity Balancing via centralized power plants Grid reinforcements Centralized energy storage
Implicit	Equation of societal benefits with private business case Future need for a flexibility market to avoid future distribution grid reinforcements Denmark as a leader in export markets	"Smart energy": decentralized energy storage, conversion of electricity to other energy sources

The scenario exercise also rendered explicit some implicit exclusions, which became even more visible in comparison with alternative scenarios by other research groups. In the iPower scenario process, the discussions on the definition of the smart grid revealed that several participants considered the smart grid vision as a step in a longer transition process towards a smart energy system. It was argued that the focus on the electricity grid would have to be extended to include the integration with the gas grid, district heating and transport—more than has been the case until now (cf. Lund et al. 2012). Our analysis shows that the boundaries of the smart grid were initially drawn around the electricity system, whereas there is increasing pressure beyond the iPower platform to draw a broader boundary including the entire energy systems (smart energy). Indeed, this distinction between the electricity system and the wider energy system might become blurred in the future if heating and transport become powered by electricity.

It is important to note that some of the ambiguities inherent in iPower derive from the original definition of the smart grid in Denmark (DEA and Energinet 2010). This definition includes links to the systems related to heating and transport but does not elaborate on them, even though a background report (EA Energianalyse and Risø DTU 2009) emphasized the socio-economic benefits of using more wind energy within the Danish borders. When wind energy is plentiful, electricity prices are low, sometimes even negative. From this perspective, it might be better to invest more in systems that use wind energy nationally even outside the electricity system, rather than giving priority to large investments in international connections. But for the TSO and the largest and most dominant DSOs and electricity traders, international integration may open more tempting possibilities for expansion, and furthermore, the idea of an integrated and liberalized European electricity market attracts political support. Moreover, in the original definition of the smart grid in Denmark (DEA and Energinet.dk 2010), the term business case is applied both as a socio-economic perspective and as a private business perspective: the two are simply considered to be synonymous. Although the formulation of the iPower platform was strongly related to DSO interests and focused primarily on developing technologies and business models to enable flexible demand, some of the participants in the scenario process actively questioned some of the basic assumptions underlying the vision. This is because the iPower project was formulated in 2010, and external conditions had changed since then.

Discussion

We have shown, through an analysis of the iPower platform and comparison with other Danish visions of the future energy system, how actors in the smart grid arena build on and propagate several explicit and implicit assumptions (cf. Truffer et al. 2008) about the smart grid of the future. Although the original proposal for the iPower project included a brief definition of the smart grid, focusing on production-controlled demand, it is interesting to note that there was initially no shared definition of the smart grid across the platform, probably due to the complexity of the Danish smart grid vision, interpreted by the diversity of the participating members ranging from large industrial companies to SMEs, including the DSOs as well as electrical engineers, social scientists and others. This finding concurs with observations by Balta-Ozkan et al. (2014) and thus reinforces an emerging view that expectations towards the smart grid can be both diverse and quite ambiguous.

From the perspective of expectation dynamics (Truffer et al. 2008; Alkemade and Suurs 2012), our analysis shows that the Danish smart grid vision has been successful in the sense that the actors succeeded in gaining public funding for exploring the vision further. To function, a vision has to be acceptable for different interests. This implies that some contradictions and dependencies on external developments are glossed over. Hence, visions and hyperbolic expectations about smart grid developments can be said to serve as aligning devices that reflect various interests, especially of powerful and important groups for innovation, although they might be contradictory. The smart grid is naturalized as the obvious solution to various problems, yet at the same time, this seemingly dominant solution is highly ambiguous and its materialization is dependent on certain surrounding conditions. The actors' awareness of several challengers suggests that the *naturalness* of smart grids is contested even within the smart grid community. As Geels and Smit (2000) cautioned, there comes a point in the innovation process when ambiguous expectations need to be clarified, concrete investments need to be prioritized and competition among different solutions becomes visible.

Our analysis of implicit and explicit assumptions shows that projects like iPower define the boundaries of the smart grid in ways that support particular institutional and ownership strategies. When the boundaries of the smart grid are defined narrowly around the power grid, other actors are excluded. This does not necessarily stop them from developing their own solutions in parallel. In Denmark, other actors related to the supply of heat, electrical cars and local zero-energy solutions have been active in developing district heating systems, biogas, co-generation, alternative transport solutions and supply networks as well as local, semi-decentralized heat pump and solar systems. New forms of distributed ownership may be part of the conflicts over system boundaries, since the electricity companies might not have an interest in heating systems or reservoirs, in which local or regional actors are keen to invest in order to reduce costs and electricity consumption (Lund et al. 2012).

Our analysis suggests that the type of scenario analysis conducted in the iPower project can offer valuable insights for large R&D platforms and smart grid development efforts more generally. The initial Danish vision (DEA and Energinet.dk 2010) was suggested many years before the need for that vision will actually arise, i.e. many years before the amount of fluctuating energy sources, electric vehicles and heat pumps actually start challenging the grid and therefore create the need for the vision to materialize. Our analysis shows that when such visions are mobilized in order to align interests to a certain line of development, their time dependency needs to be considered. In some cases with long time horizons, one vision may not suffice or may even result in the activation of challengers to the vision.

While the iPower scenario process served to surface some implicit assumptions and exclusions, a cross-country comparison might highlight further issues that might be overlooked in national smart grid development platforms. For example, Balta-Ozkan et al. (2014) report on a comprehensive UK smart grid scenario project including a literature review (Xenias et al. 2014) and using a variety of qualitative and quantitative methods. It is beyond the scope of this paper to summarize the UK scenarios, but it is interesting to compare the issues that are dealt with in this project with those in our study. There are many similarities in the identification of drivers, supporters and critical issues, but some differences can be found. First, as a natural consequence of the UK being a much larger country than Denmark, there is more discussion on spatial variation with regard to the implementation of the functions of the smart grid. Second, distributional impacts are highlighted in the UK while they are nearly absent in the Danish material. It is argued that "the distribution of benefits is unlikely to be uniform within and across different geographical settings" (Balta-Ozkan et al. 2014: 3), and it is considered important to ensure more equitable outcomes. The difference can relate to the fact that inequalities are more pronounced in the UK and energy poverty is widely discussed, but it can be argued that distributional issues ought to become more prominent in the Danish context, because the combination of privatization and the smart grid makes some consumers more useful to electricity companies than others and thus encourages less equitable outcomes. Third, the process of privatization and liberalization of the electricity sector started much earlier in the UK than in Denmark, and for the distribution network operators, the regulatory framework has rewarded gradual increases in efficiency rather than innovation, resulting in a dramatic fall in research and development and a skills shortfall in the sector. For the promotion of the smart grid agenda, there is much focus on the need to change this situation—a point that may serve as a relevant warning in a Danish context.

There is hence much scope for further research. Our analysis highlights some of the benefits and limitations of a scenario exercise in exposing implicit expectations and questioning system boundaries. Further work is needed to make scenarios more helpful for this kind of reflection. Scenario processes might have different outcomes in different settings or using different methods. For example, one avenue for further research considered in iPower is to quantify the scenario drivers, which might render potential competition among solutions more visible. Within iPower, further work is underway to conduct socio-economic investor evaluations on the basis of the scenario analysis.

Further limitations and research needs ensue from our particular perspective, which is informed by the literatures on expectations in innovation (Geels and Smit 2000; Borup et al. 2006; Truffer et al. 2008). One potential avenue could be to compare and combine this analysis of the actors' expectations more systematically with techno-economic analyses of the future electricity and energy system. Our analysis highlights problematic areas that might be overlooked in the initial smart grid hype, for example, the basic smart grid coordination problem: there are multiple actors involved, and those who have to make investments are not necessarily the same actors who will extract value from the investments. Further research is needed to identify in detail how this problem could be mitigated within the different institutional and regulatory regimes existing in Europe. Similarly, we have highlighted competition for the market for flexibility services as a major concern for smart grid investment. Further research might quantify the relationship between flexibility and electricity conservation in influencing total energy demand, or the relations between centralized and decentralized power production (cf. Bolton and Foxon 2011) in various smart grid configurations.

Conclusions and policy implications

Our findings show that the smart grid hype embodies several implicit expectations that guide initial research and investment and attract companies to the field, as evidenced by the wide membership of the iPower platform. A scenario process such as that demonstrated in the case of the iPower project can serve to articulate some of these implicit assumptions and help actors to navigate the ongoing transition. Researchers and businesses working to create the smart grid need to understand competitors and delayers, and a scenario process can help to articulate the conditionality of the system that participants are building. However, researchers and businesses with a commitment to certain technologies might not be eager to question some of the assumptions underlying their work, because the ambiguity of smart grid expectations also serves to legitimate existing courses of action and to align the interests of divergent actors. Hence, their R&D work may create implicit boundaries vis-à-vis other relevant technologies and may struggle to question certain underlying assumptions, such as the equation of the *societal benefit* and *entrepreneurial business case* in the case of the Danish smart grid vision.

Policymakers play a key role in the shaping of the future smart grid. They fund research and development platforms and shape expectations through policy papers, regulations and incentives. On the basis of our analysis, European policymakers might consider how their (intentional or unintentional) choices serve to create or maintain certain boundaries for the European smart grid development: for example, an exclusive focus on electricity within the broader context of a sustainable energy system. When visions are mobilized in order to align interests to a certain line of development, expectations concerning timing should be taken into consideration. When time horizons are long, visions might need to be periodically revised. Since the smart grid project is a response to future needs in the electricity system, it is important to keep an eye on competing solutions to the problems that the smart grid aims to solve.

Policymakers might also seriously consider the viability of the smart grid within a liberalized electricity system, given that socio-economic benefits of a smart grid might not translate directly into a private business case. Ambiguous concepts like the smart grid serve to align the interests of several different actors. This is both their strength and their weakness. As serious investment starts being made in the smart grid, solutions like the supergrid, flexible demand and a broader smart energy system will start competing with each other. At this point, at the latest, the ambiguity will necessarily start to dissolve and conflicts of interest will become more apparent. Policymakers would do well to anticipate such conflicts and prepare to specify their visions and prioritize.

Acknowledgments The research reported in this paper has been supported by the iPower project. We gratefully acknowledge the valuable comments provided by three anonymous reviewers.

References

Alkemade, F., & Suurs, R. A. (2012). Patterns of expectations for emerging sustainable technologies. *Technological Forecasting and Social Change, 79*(3), 448–456.

Andersen, P. D. & Jørgensen, B. H. (2001). *Grundnotat om metoder indenfor teknologisk fremsyn*. Note prepared for The Danish Agency for Trade and Industry by Research Center Risø.

Balta-Ozkan, N., Watson, T., Connor, P., Axon, C., Whitmarsh, L., Davidson, R., Spence, A., Baker, P., Xenias, D., Cipcigan, L., & Taylor, G. (2014). *Scenarios for the development of smart grids in the UK—synthesis report*. London: UKERC.

Bolton, R., & Foxon, T. J. (2011). Governing infrastructure networks for a low carbon economy: co-evolution of technologies and institutions in UK electricity distribution networks. *Competition and Regulation in Network Industries, 12*(1), 2–27.

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology Analysis & Strategic Management, 18*(3–4), 285–298.

Danish Ministry of Climate, Energy and Building (2011). *Faktaark til Vores Energi, november 2011.* Last observed July 16th 2013 at: http://www.ens.dk/sites/ens.dk/files/politik/dansk-klima-energipolitik/regeringens-klima-energipolitik/vores-energi/faktaark-energi-og-klimapolitiske-maal-final.pdf.

Darby, S., Strömbäck, J., & Wilks, M. (2013). Potential carbon impacts of smart grid development in six European countries. *Energy Efficiency*, 1–15.

DEA (Danish Energy Association) & Energinet.dk (2010). Smart grid in Denmark.

DEA (Danish Energy Association) & Energinet.dk (2012). Smart grid in Denmark 2.0.

DECC & Ofgem (2014). *Smart Grid Vision and Routemap*. UK Department of Energy and Climate Change and Ofgem. Online https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/285417/Smart_Grid_Vision_and_RoutemapFINAL.pdf.

DR (2014). *Danske vindmøller sætter ny verdensrekord.* Last observed March 27th 2014 at: http://www.dr.dk/Nyheder/Regionale/MidtVest/2014/01/13/173345.htm.

Du, W., Pruyit, E., Slootweg, J.G., Thissen, W.A.H. & Walker, W.E. (2009) Transition to 'smart' distribution grid: strategic planning using a scenario approach. 20th International Conference on Electricity Distribution Prague, 8–11 June 2009 http://www.cired.net/publications/cired2009/pdfs/CIRED2009_0825_Paper.pdf.

EC (2011) *Smart grids: from innovation to deployment.* Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission SEC(2011) 463 final.

Energinet.dk (2007). *Scenarierapport, fase 1 – arbejdspapir.* Published in Danish by Energinet.dk February 2007. Last observed March 26th 2014 at: http://energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Scenarierapport%20fase%201.pdf.

Energinet.dk (2013). Film on smart grid: https://www.energinet.dk/DA/FORSKNING/Energinet-dks-forskning-og-udvikling/Smart-Grid/Sider/Film-Smart-Grid-Danmark.aspx. Last observed May 24th 2014.

Erlinghagen, S., & Markard, J. (2012). Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. *Energy Policy, 51*, 895–906.

EurElectric (2010). 10 steps to smart grid. EURELECTRIC DSOs' ten-year roadmap for smart grid deployment in the EU. EurElectric. Online: http://www.eurelectric.org/media/26140/broch.10steps_lr-2011-030-0304-01-e.pdf

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. *Energy Policy, 52*, 10–24.

Foxon, T. J., Pearson, P. J., Arapostathis, S., Carlsson-Hyslop, A., & Thornton, J. (2013). Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future. *Energy Policy, 52*, 146–158.

Geels, F. W., & Smit, W. A. (2000). Failed technology futures: pitfalls and lessons from a historical survey. *Futures, 32*(9), 867–885.

Giordano, V., & Fulli, G. (2012). A business case for smart grid technologies: a systemic perspective. *Energy Policy, 40*, 252–259.

Harbo, S., Biegel, B., Meibom, P., Hansen, L. H., Andersen, P. & Stoustrup, J. (2013). *Contracting flexibility services*. In 36th Annual IAEE International Conference, Daegu, Korea, 16–20 June.

Heijden, K. (1998). *Scenario development*. Chapter 12 from the book: 'Scenarios – The Art of Strategic Conversation'. John Wiley & Sons, p. 219–272.

Honebein, P. C., Cammarano, R. F., & Boice, C. (2011). Building a social roadmap for the smart grid. *The Electricity Journal, 24*(4), 78–85.

iPower (2013a). *iPower's strategic scenarios for the adoption of smart grid in Denmark*. Last observed February 28th 2014 at: http://issuu.com/ti_molu/docs/ipower_strategic_scenarios_-_public

iPower (2013b). *Determining factors for the adoption of smart grid—background report*. So far published internally in the iPower consortium.

iPower (2014). *Strategic platform for innovation and research in intelligent power*. Last observed February 28th 2014 at: http://www.ipower-net.dk/.

Joint Research Centre (2014). *Smart grid projects in Europe*. Last observed February 28th 2014 at: http://ses.jrc.ec.europa.eu/smart-grid-projects-europe.

Jonsson, D. K., Gustafsson, S., Wangel, J., Höjer, M., Lundqvist, P., & Svane, Ö. (2011). Energy at your service: highlighting energy usage systems in the context of energy efficiency analysis. *Energy Efficiency, 4*(3), 355–369.

Jørgensen, U. (2012). Mapping and navigating transitions—the multi-level perspective compared with arenas of development. *Research Policy, 41*(6), 996–1010.

Klimakommissionen (2010). Green energy—the road to a Danish energy system without fossil fuels. Summary of the work, results and recommendations of the Danish Commission on Climate Change Policy.

Kwon, P. S., & Østergaard, P. A. (2012). Comparison of future energy scenarios for Denmark: IDA 2050, CEESA (Coherent Energy and Environmental System Analysis), and climate commission 2050. *Energy, 46*, 275–282.

Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., & Connolly, D. (2012). From electricity smart grids to smart energy systems—a market operation based approach and understanding. *Energy, 42*, 96–102.

Martiskainen, M., & Coburn, J. (2011). The role of information and communication technologies (ICTs) in household energy consumption—prospects for the UK. *Energy Efficiency, 4*(2), 209–221.

Moura, P. S., López, G. L., Moreno, J. I., & De Almeida, A. T. (2013). The role of smart grids to foster energy efficiency. *Energy Efficiency, 6*(4), 621–639.

EA Energianalyse & Risø DTU (2009). *Bedre integration af vind*. Udført for Energistyrelsen og Skatteministeriet.

Truffer, B., Voß, J. P., & Konrad, K. (2008). Mapping expectations for system transformations: lessons from sustainability foresight in German utility sectors. *Technological Forecasting and Social Change, 75*(9), 1360–1372.

Udvalg for el-reguleringseftersynet (2014). *En fremtidssikret regulering af elsektoren*. Energistyrelsen, København.

Verbong, G. P., & Geels, F. W. (2010). Exploring sustainability transitions in the electricity sector with socio-technical pathways. *Technological Forecasting and Social Change, 77*(8), 1214–1221.

Verbong, G. P., Beemsterboer, S., & Sengers, F. (2013). Smart grids or smart users? Involving users in developing a low carbon electricity economy. *Energy Policy, 52*, 117–125.

Xenias, D., Axon, C., Balta-Ozkan, N., Cipcigan, L. M., Connor, P., Davidson, R., Spence, A., Taylor, G., Whitmarsh, L. E. (2014). *Scenarios for the development of smart grids in the UK: literature review*. [Working Paper]. London: UKERC. Available at: http://www.ukerc.ac.uk/support/tiki-download_file.