Renewable Energy 81 (2015) 89–102

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

UK smart grid development: An expert assessment of the benefits, pitfalls and functions

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ARTICLE INFO

Article history:
Received 1 October 2014
Accepted 7 March 2015
Available online 27 March 2015

Keywords:
Smart grid
Policy Delphi
Electricity market regulation
Active network management
Demand side response
Return on investment

ABSTRACT

Making electricity grids smarter is a challenging, long-term, and ambitious process. It consists of many possible transitions and involves many actors relevant to existing and potential functions of the grid. We applied a two round Policy Delphi process with a range of sectoral experts who discussed important drivers, barriers, benefits, risks and expected functions of smarter grids, to inform the development of smarter grids. Our analysis of these expert views indicates broad consensus of the necessity for smarter grids, particularly for economic and environmental reasons; yet stakeholders also associated a range of risks and barriers such as lack of investment, disengaged consumers, complexity and data privacy with measures to make the grid smarter. Different methods for implementing smarter grid functions were considered, all thought to be more likely in urban settings. Implications for policy and future research are considered.

1. Introduction and aims

1.1. Definitions and drivers of smart grids

The need to decarbonise electricity supply, maintain and improve security of supply while reducing fossil fuel imports in a world of rising prices is propelling the rapid adoption of technologies which place additional stress on traditional electricity networks [1]. Expansion of electric vehicles and heat pumps particularly, have the potential to substantially increase load across distribution networks, and the associated changes to networks will render current solutions expensive and unreliable [2,3]. Intermittent renewable energy sources of electricity such as wind and solar, are already major elements of generation in Germany, Denmark and elsewhere and look set to increase internationally [4–6] and is supported by national [e.g. [7,8]] and international policy drivers [e.g. [9,10]]. Innovation is therefore required for smarter solutions to ensure systems reliability in the face of increased supply and demand volatility. The International Energy Agency [11] estimated that Europe will have to invest €1.5 trillion in the period 2007–2030 to renew the electricity system [12] and early investment is likely to reap significant long-term savings. Smarter network management technologies might save up to £10bn in the UK alone, even if the uptake of low-carbon technologies remains low [2] and considerably more if uptake is high. These savings come from opening up cheaper options than traditional expansion of wires and reducing or delaying the need for capital investment. Smarter electricity delivery and usage appears to be an integral part of the transition to a low-carbon energy future [13].

However, there are significant challenges associated with a move towards smarter grids (SGs). Regulatory systems developed largely to serve the needs of centralised generation and transmission, and electricity networks evolved within this context; this can mean barriers for more distributed generation, its regulation and monetisation [14,15]. Moreover, regulatory change will be needed so as to achieve ambitious carbon targets set, and to allow the creation of a sophisticated market space that will allow smarter products and services [15].

This process is hampered by the absence of a commonly accepted definition of what a SG is, with different working

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http://dx.doi.org/10.1016/j.renene.2015.03.016

Acronyms

DECC	Department of Energy and Climate Change
DNO	Distribution Network Operator
DSM	Demand Side Management
DSR	Demand Side Response
ESI	Energy Supply Industry
GB	Great Britain
Ofgem	Office of Gas and Electricity Markets
RIIO	Revenue = Incentives + Innovation + Outputs (a network regulation mechanism)
SG	Smarter Grid
SO	System Operator
TSO	Transmission System Operator

definitions across different territories and organisations. Widely accepted SG components tend to include efficient management of supply (including intermittent supply), two-way communication between the producer and user of electricity, and the use of IT technology to respond to and manage demand, and ensure safe and secure electricity distribution. The International Electrotechnical Commission view SG in terms of modernisation [16]; some US definitions depict SG largely in terms of technical solutions [17]; elsewhere the wider social, environmental, economic and behavioural issues are also considered [18,19]. We favour the definition provided by the Smart Grids European Technology Platform: "*electricity networks that can intelligently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies*" [[19], p. 6]. This reflects both the complexity of the system and potential for unknowns in different areas to interact with surprising and substantial implications.

The very lack of a clear definition points to the fluid and dynamic nature of this field. The use of scenarios in different energy sectors has helped guide the response of relevant players [e.g. [20]]. In this paper, we report on a stakeholder elicitation study, using the Policy Delphi technique, to inform the creation of a set of scenarios on UK SG development.

1.2. Uncertainty in the evolving UK electricity supply industry (ESI)

The drivers for SG are diverse. Substantial intermittent generation may emerge from onshore and offshore wind energy, and other renewables; these may range from large developments directly connecting 500 MW+ to the transmission grid, to 1 kW at remote parts of a distribution network. It is impossible to accurately predict the deployment rates of these technologies, their volumes or locations. This impedes the planning of supporting network infrastructure, and creates a difficult situation where: (a) infrastructure extension is needed for developers to plan and invest in new generating capacity, (b) rapid addition of generation, e.g. large wind farms in remote locations, cannot rely on existing networks and (c) network companies must consider whether new extensions will be used and provide a return since their income depends on usage.

The transmission network companies and the UK energy regulator –Ofgem-have begun to respond to these evolving problems but neither Ofgem nor the Distribution Network Operators (DNOs) are well suited to deal with such planning, which requires more innovation and is riskier than it has been in the past. Ofgem is also responsible for protecting consumers by ensuring additional transmission costs are minimised; furthermore, the energy sector is subject to unpredictability and thus uncertainty regarding investment outcomes. This implies risk to investors, and the greater the uncertainty the more risk may be engendered. This increases the required return on investment and thus overall allowable costs to be passed to the consumer, and Ofgem may need to change their approach to allow investment in different and riskier network operator behaviours. It is also apparent that large volumes of intermittent generation will require the System Operator (SO) to consider different approaches to network balancing.

A similar problem impacts demand. There is uncertainty over future demand changes and whether energy efficiency programmes will prove effective. Some assessments suggest UK energy decarbonisation will only be possible with programmes to electrify both heat (i.e. through heat pumps) and transport provision [21–23]. One UK overview of scenarios for decarbonisation via electrification suggested a doubling in peak demand by 2050 [24]. Demand, of course, is also dependent on public acceptance and uptake of electric transport and heat options, which is not assured and may prove more difficult than anticipated [25]. Such changes, if they happen, would mean substantial challenges for DNOs and the SO. Smart technologies, with their potential to allow greater controllability and knowledge across networks are essential to allowing DNOs to actively manage networks and prevent sudden load shifts leading to grid failures. The scale of new stressors on the networks makes smarter approaches essential in countries like the UK.

Addressing these issues the UK government introduced a SG routemap [26], building on the earlier Electricity Networks Strategy Group routemap [27], which had already been partly superseded by the introduction of RIIO [28,29] and the ongoing Electricity Market Reform (EMR) [29,30]. The DECC routemap sets out three key stages in UK SG development as foreseen by the UK Government [24]: 2014–2020: Development (including smart meter rollout); 2020–2030: Rollout; and 2030–2050: Developed Phase (where IP exploitation and consumer benefits are realised). This model requires initial innovation but seems limited on continuous innovation beyond the initial phases. It notes, but does not explore, the risks and uncertainties of the evolution of the UK's future ESI. National Grid [31] goes further in considering the different elements that will increase smartness across the functions of the UK ESI and in identifying the political, economic, social, and technological uncertainties that will influence their development. Their assessment implies a different picture and timeframe for network change, with both (a) evolving system demands and (b) corresponding continuing innovation, extending to 2050. Other work explores SG development in the context of energy system change [e.g. 32].

While these efforts to define SG uncertainties and map future development are important, they give little attention to behavioural or spatial dynamics or to the range of stakeholder perspectives on energy system change. Our project aimed to address these important deficits in the current literature by producing a detailed, interdisciplinary examination of SG development, incorporating evolving system demands and innovation, through a robust stakeholder elicitation methodology.

1.3. Smart grid stakeholders

The wide and fluid definition of what can be included in SGs creates a wide net of stakeholders that must be considered as likely to impact or be impacted by SG development. Organisations already active in generation, supply, transmission and distribution will be central to any reshaping of their sectors. The networks and SO will be most strongly impacted by the changes, since they will have to manage the changing demands on the system, deal with increased risk, and manage increased investment in innovation.

Many energy consumers (industry excepted) currently take a passive role in overseeing and managing their energy use. Many models for future SG suggest Demand Side Management (DSM) will place an increasingly important role in helping the SO and the DNOs to deal with large volumes of intermittent power. This may mean domestic and other consumers, who have considered potential consumer impacts of the evolving energy sector, play a much more active role than is currently the case, making them a key stakeholder group [33,34]. Their engagement or otherwise may be a significant limiting or driving factor as regards DSM and network management, as well as the market success or otherwise of new energy services.

The UK also has a specific barrier to SG development stemming from the particular structure of its network regulation: while most EU Member States will see Distribution System Operator (DSO) driven smart meter rollouts, it will be UK suppliers that will provide and pay for smart meters and data collection. Since UK DNOs stand to gain many of the benefits from complex smart meter functions, while the suppliers are interested in only limited functions, there is mismatch between costs and benefits, representing a market failure which may result in benefits remaining uncaptured. This has already influenced the specification for smart meters with DNOs initially slower to react, though they are now more active through the Department of Energy and Climate Change (DECC)/Ofgem Smart Grid Forum (SGF) and trade bodies.

Since the drivers for SG derive largely from government policy addressing climate change and energy security, the perspective of policy-makers is key to future SG development. The variety of drivers as well as the need for 'joined-up' solutions requires multiple UK government departments including groups within DECC with different responsibilities on renewable electricity and heat, and the Department for Transport's Office for Low Emission Vehicles (OLEV). A key stakeholder is also Ofgem, who are responsible for reform of the instruments that delineate the electricity market and for network incentives; their changes will shape the framework in which SGs emerge and the services they might provide.

Notably, a potential outcome of SG development is that the industry will be opened up to new services and new entrants, increasing uncertainty in the future development in this area making it impossible to consult with these stakeholders in advance. Perspective on these sectors was sought directly from companies active in this field, from consultants and from trade organisations such as Smart Grid GB, the British Electrotechnical and Allied Manufacturer's Association, the Electricity Networks Association and Energy UK.

Together with academic experts, these stakeholder groups provide unique insights into the development of SGs, an assessment of their drivers, barriers, benefits, risks, and desired functions, which are particularly important for the later development of scenarios for the future of SGs. In the following section, we outline our methodology for eliciting the views of these diverse groups on this highly pressing but uncertain field.

2. Methodology

To address complex issues such as the future of smarter energy grids, participatory methods are often employed. Delphi is one such method, which aims at involving stakeholders and facilitating knowledge co-production, by narrowing down discussions to the most pertinent and significant issues that are perceived to impact on the UK smart grid development.

2.1. The Delphi method

The Delphi approach uses an iterative approach; participants provide their responses, and are then typically shown the summarised results in a subsequent round of consultation [35]. The purpose is to consolidate a wide range of opinions to fewer and more realistic themes, ideally reaching consensus. Data is collected anonymously so that participants can provide their uninhibited views, thus contrasting with alternative approaches, such as academic dissemination and data collection via expert interviews or focus groups. The advantage of anonymous reporting is that participants are not tempted to follow the opinion of established figures in their area [36].

Several sizeable projects [20,37–40] have used the Delphi method (or variants, such as Policy Delphi) to elicit stakeholder and/or expert views on energy system futures. Although not all energy scenarios are developed through Delphi-type techniques [e.g. [41]], the advantages of Delphi match the requirements of policy research as this method can (a) capture a broad range of expert and non-expert views on (b) a young field (i.e. with little extant literature), rapidly developing, controversial [42] and/or (c) where long-term predictions are required [43]. Delphi is often combined with other methods [39,43], including workshops, and scenario development [37,43] as in our case [see [44] for full project report].

2.2. Policy Delphi

Policy Delphi [Turoff, 1970, in [35]] was developed from Delphi, and similarly uses an iterative method in which there are more than one (usually two or three) rounds of consultation, in order to identify and understand divergent opinions. In the first round, questions are often formulated as statements about the state/performance/penetration of a particular technology, e.g. '50% of vehicles in the EU produce zero emissions (other than CO_2 and water)' [37]. Questions may also be broader or open-ended; e.g. 'List four trends or issues and their driving causes that you believe may influence the sector up to 2015'. Responses may focus on impacts, timing, feasibility, and so on [39,43]. In the second (and potentially third) round, participants are typically shown the results from the previous round and respond to them, often by providing a revised response. The Policy Delphi differs from the Delphi in that it does not seek to reach a consensus but rather seeks to contrast opinion and highlight a range of different viewpoints on an issue [35].

2.3. Current research

We adopted a combination of traditional and Policy Delphi, and developed an online survey using Qualtrics software for the anonymised collection of personal opinions of experts, involved in, and covering different aspects of, the development and implementation of SGs. Through relevant networks and via internet and literature searches, we identified approximately 200 experts including representatives from academia, industry, policy and the third sector. These experts were contacted by telephone or email by the researchers personally, and were invited to participate in our survey.

The first round in April 2012 involved 77 experts (46 male, 31 female). Around half were academics and network operators, with the remainder spanning policy-makers, representatives of communities with smart grid experience, suppliers/generators, interest groups, consultants and others. The same group of experts was invited to participate in the second round in September 2012; this time 44 (30 male, 14 female) completed the survey. With respect to expertise, the sample (see Fig. 1) included a higher proportion of industry and engineering experts, reflecting the higher proportion of SG expertise residing in industry and academia than elsewhere. We compared response differences by expertise, and there were only minor differences (please refer to Appendix C for this analysis), which did not warrant the exclusion of any particular subgroup from the analysis.

In the first round, participants completed an online survey comprising sections on demographics, identification of expected SG benefits and pitfalls, their functions, and key issues which could significantly impact them (for a full list of the questions please refer to online supplemental materials). The survey items were developed through detailed literature reviews and expert interviews conducted in order to expose the key technical, social, and policy issues [see [44]].

In the second round, the survey reflected the SG functions that were judged as 'essential' in round 1, as well as demographic information back to participants. This round aimed at capturing dependencies surrounding each essential function, and thus the questions asked experts to identify the critical steps required for the implementation of each of the six essential functions. In addition, participants were asked to choose among possible ways of implementing each of the six key functions, as well as to indicate how likely each function was to be implemented in (a) an urban and (b) a rural setting (for a full list of the questions please refer to Appendix A). These findings are presented in Results.

3. Results and discussion

We present and discuss the benefits and pitfalls, the drivers and barriers, the factors most important for making the grid smarter, and the functions that smart grids should possess or be able to deliver. We thematically coded participants' responses in accordance with McLeod's [45] four-phase model: all open-ended responses were assigned thematic codes; these codes were aggregated into meaningful thematic categories. The process was repeated two to four times (depending on the question and variability of responses), until clearly discernible categories emerged and were agreed upon between two independent coders. Finally, these categories were organised by frequency of occurrence.

3.1. Drivers and barriers for SG development

We first explored the impetus for SGs and the ranked survey results for the main drivers for the development of SGs are summarised in Table 1. The top three identified drivers represented 30% of responses. First was the *integration of renewables* onto the existing network and subsequent need for intermittent energy management and integration. *Clarity of long-term government policy* ranked second and spans several areas including carbon targets and energy production, consistency, and long-term commitment. The third driver was *uptake of emerging devices* that would necessitate active network management. The complete list is shown in Table B.2a and Table B2.b.

The theme of the most cited barriers to a smarter grid was inertia or unwillingness of stakeholders to engage with the smartening process. *Customer disengagement* was the most frequently cited barrier, but was less well defined than other themes in participants' comments and may therefore represent perceptions and expectations for the role of customers. The second barrier was *unclear policy*. Its reciprocal, *strong policy*, was also cited as a driver for smarter grids, which emphasises the perceived importance of coordination across the whole of Government in SG development. *Industry inertia and investment costs* were considered equal as barriers. Lack of investment and implementation cost were also identified as major pitfalls.

Table 1
Perceived drivers for, and barriers to, smarter grids.

	Rank	Votes (#)	Votes (%)
Perceived driver			
Increase renewables integration	1	12	12%
Clear Government policy and leadership	2	10	10%
High uptake of PV, EV, and heat pumps	3	8	8%
Perceived barrier			
Customer disengagement/resistance	1	22	25%
Unclear policy, governance, and changing targets	2	17	19%
Industry inertia and resistance	3=	11	13%
Investment and costs	3=	11	13%

3.2. Benefits and pitfalls of SG development

The benefits and pitfalls considered possible outcomes of developing a smarter grid, and were therefore different to drivers and barriers. This distinction was also evident in the vast majority of participants' comments. The complete ranked survey results for the expected SG benefits and pitfalls are shown in Table B.1a and Table B.1b respectively, and summarised in Table 2. The top three perceived benefits accounted for 39% of responses, with *efficiency* and *loss reduction* — making best use of existing assets — considered most important. Second was *cost reduction*; respondents considered that savings would arise at different levels of the system once smarter solutions were in place. However, comments concentrated on extending asset lifetimes to lower investment costs or that smart solutions might be cheaper than network reinforcement in the face of growing power demand. Improved efficiency was thought by respondents to assist in both current and future generation, power delivery, and asset utilisation throughout the system. Technologies and practices grouped as *active network management* were the third most significant expected benefit. These included better fault management, flexibility, and improvements in control and reliability. Facilitation of renewables and the reduction of CO_2 emissions ranked fourth, accounting for 8% of the responses, reaffirming that renewable generation both pushes for and benefits from smarter grids.

The most frequently cited pitfall of SGs implementation was *investment* and relevant issues. This included risk, the expense and availability of available capital, and the quantity of capital required in a relatively short period of time. Some respondents considered SG technologies expensive to implement, thus the rates of return on investment were likely to be less attractive. The second most significant perceived pitfall was *complexity* for both customers and the technical stakeholders in the energy system. Respondents regarded SGs as complex to design, implement, operate and

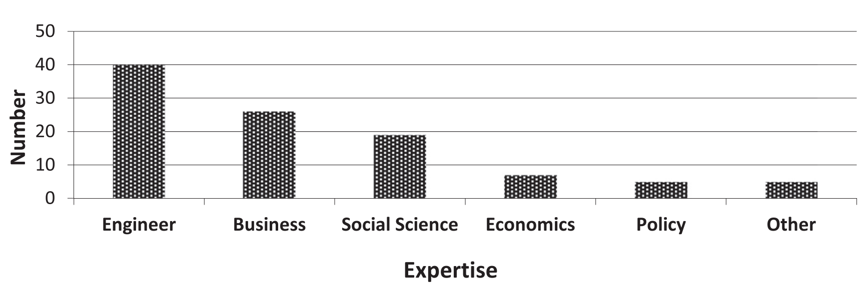

Fig. 1. Participants' areas of expertise.

Table 2
Benefits and pitfalls of SGs identified by stakeholders.

	Rank	Votes (#)	Votes (%)
Perceived or expected benefit			
Efficiency/loss reduction	1	32	15%
Cost reduction	2	31	14%
Enable active network management	3	21	10%
Perceived or expected pitfall			
Investment issues	1	30	15%
Complexity of proposed solutions	2	24	12%
Disengaged/uncooperative customers and stakeholders	3	21	11%

regulate. The third was the risk that customers (residential or commercial) would be *unresponsive or uncooperative*. Although the comments did not always identify why customers might not engage or what exactly would be the result of not engaging, the sensitivity of customer response of engagement strategies was cited as a concern-the issue of customer engagement was also mentioned as a factor influencing SG development (see Section 3.3). These pitfalls account for 38% of responses with the remainder covering a very wide range of issues.

3.3. Factors for SG development

Participants reflected on the way that eight different factors, identified within the literature and interviews, would impact on the process of making the grid smarter [44]. The results summary is shown in Table 3, with the full lists in corresponding tables in Appendix B.

3.3.1. Standards

The top three themes for this category were ICT-related: *smart metering*, *communication protocols*, and *data exchange standards*. The first relate to issues such as the implementation, design and functions of smart meters. Communication protocol issues spanned the requirements at all levels of SG, including substation communications. A strongly emerging related topic concerned standards for data exchange and control of devices and appliances, including specifications and functionalities for automated DSM. It is possible that these results (representing 66% of responses) reflect that the smart meter agenda in the UK is retail-led which was a clear concern amongst DNOs and ICT specialists.

3.3.2. Technical issues

The first theme – *communications* – was not always well defined i.e. some participants only reported "communication protocols" or "communication technology" without further details. For other respondents it was clearly about deployment of communication technology, infrastructure and protocols. *Active network management* was the second most important dimension, and the third being *condition and voltage monitoring*. The three most cited responses accounted for 63% of all responses.

3.3.3. Data handling

Data protection/security and *privacy* were the most cited responses. There was concern of the limits that might apply to the volume and nature of data which Government/Ofgem allow to be collected, transmitted and stored outside consumers' control, and who would have access to this data. There was concern too that Government choices could affect the usefulness of the data to network operators, the services that thus might be offered to consumers, and consumers' level of control over their energy use and changes in their demand. The question of *public acceptability* included concerns over public opinion and the role of the media and transparency. The top three items accounted for 44% of all responses.

3.3.4. Market structure

There was a wide variety of less well-structured responses to this question (the top two responses only accounted for a quarter of the total). The dominant theme was *fragmentation*, whether within the industry, markets, incentives, confused responsibilities, or policy. *Lack of co-operation* was frequently cited in these contexts. The separation between the Transmission System Operator (TSO), the DNOs, metering, and supplier activities was considered to have negative effects. Respondents also suggested that it was the responsibility of Government to take action and enforce cooperation.

3.3.5. Regulation

Effective commercial arrangements and *pricing* included the development of fair energy-use tariffs for consumers in fuel poverty. The regulatory issues for *DNO structure* and operation included investment and the ownership of generation. Some participants considered that the regulatory boundaries of DNOs need to be relaxed to allow for greater interaction with customers if SGs are to be successful. Related to these structural issues, *incentives and alternative revenue streams* included the need for incentives for networks to work with each in the "*best interests of the nation*", and the view that network regulation incentives such as the Low Carbon Networks Fund (LCNF) will mostly encourage piecemeal solutions in the absence of a clear national strategy. These three represented 47% of all responses.

3.3.6. Co-ordination

This question referred to the relationship between DECC and Ofgem. Three issues were cited more often, but accounted for only 33% of all responses, indicating a wide range of differing points raised. Participants considered that effective SG development required DECC and Ofgem *agree common aims*, particularly on policy, regulation and strategy. One respondent summed up this issue as "*a clash between incentives for co-ordination versus those for competition*". The clear message was the need for consistency and long-term vision; which also emerged when considering investment issues. The specific issue of the smart metering roll-out reflected concerns contemporary with the survey. Whilst it is symptomatic of a lack of coordination, it is a small element of the DECC/Ofgem relationship. The issue is characterised as a broken value chain problem [46,47].

3.3.7. Customer engagement

Education and awareness about SGs accounted for 39% of responses. Promoting understanding of the potential advantages of SGs, as opposed to negative issues portrayed in the media, was considered essential by many participants. We found that uncertainty about *customers' willingness to participate* in demand-shifting in response to tariffs (and similar issues) and the *potential for cost reflective pricing* as an incentive for behaviour change were also important. These three items together accounted for 69% of all responses. Although other studies [e.g. 48–51] identified trust between suppliers and customers as significant, this did not emerge in this section, which we attribute to the composition of our sample; a higher representation of consumer groups may have altered this result significantly. This highlights the importance of early and meaningful public engagement with policymaking.

3.3.8. Investment

Evidence from several survey questions shows that investment issues are one of the most important factors for the successful implementation of SGs. The key for many participants was *policy*

Table 3
Summary of the ranked responses for the factors that are expected to influence SG development. The full listing for each factor is given in Appendix B, Tables B.3a – B.3h.

	Rank	Votes (#)	Votes (%)
Standards (Table B.3a)			
Smart metering	1	14	24%
Communication protocols	2=	12	21%
Device/appliance data exchange and controls	2=	12	21%
Technical issues (Table B.3b)			
Communications	1	16	28%
Active network management	2	13	23%
Condition and voltage monitoring	3	7	12%
Data handling (Table B.3c)			
Data protection/security	1	13	21%
Privacy guarantees	2	8	13%
Public acceptability/trust	3	6	10%
Market structure (Table B.3d)			
Lack of cooperation between DNOs and suppliers	1=	7	13%
Sector fragmentation	1=	7	13%
Government intervention to enforce changes	3=	3	5%
Development of demand/storage/EV/heat markets	3=	3	5%
Pricing structures	3=	3	5%
Regulation to encourage DNO participation	3=	3	5%
Regulation (Table B.3e)			
Effective commercial arrangements and pricing	1	11	20%
Transform DNO structure/operation	2	10	18%
Incentivise cooperation and alternative revenues	3	5	9%
Co-ordination (Table B.3f)			
Smart metering	1=	5	11%
Align goals and objectives	1=	5	11%
Align incentives with objectives	1=	5	11%
Customer engagement (Table B.3g)			
Customer and public education/awareness	1	25	39%
Customer willingness to comply/share data/shift demand	2	14	22%
Pricing	3	5	8%
Investment (Table B.3h)			
Long-term regulation/policy certainty/objectives	1	18	36%
Uncertain ROI	2	9	18%
New modes of financing/business models	3=	4	8%
New value delivery mechanisms (e.g. flexibility)	3=	4	8%

stability to enable investment, leading to greater certainty of return on investment. This can be interpreted as *risk aversion* on the part of the industry as a whole, and is reflected within *industry inertia* in the most cited barriers to SG development (Table 2). The message was clear with the top responses accounting for 70% of all responses. Investment issues were also cited as the greatest potential pitfall for SGs (Table 1), reinforcing the pivotal role of this factor for SG development.

3.4. SG functions and their critical dependencies

We elicited participants' rankings of pre-selected expected and possible functions of SGs (Delphi, round 1). Participants were provided with a list of 20 possible functions, to be classified as Essential, Desirable, Not important or No opinion. The voting results (Table B 3i, Appendix B) were clustered according to the ‘essential’ score using the k-means algorithm for three clusters. The ‘Essential’ score decreases as the ‘Desirable’ score increases with an R-squared value of 0.89, indicating the overall ordering of functions is reasonable. Respondents were given an open-ended question of whether there were any further functions which they considered that were not covered by our list. The ability to facilitate energy storage (of any scale) was spontaneously cited by nine respondents, and can be seen as an essential component of power systems with high levels of renewable generation [52]. Energy storage was thus added to the list of essential functions. Of the listed functions, five were chosen as essential by over 70% of experts and were voted ‘not important’ by zero respondents, indicating a degree of consensus (Table 4).

In the second round of the Delphi process, participants were asked what critical step(s) would enable the ‘Essential’ functions (Table 5) and the likelihood of that critical step being implemented (Fig. 2). This was intended to capture the critical dependencies between functions and their pre-requisites, and the strength of this dependency. It did not give an exact probability for each function being implemented, but the commentaries received gave insight into the building blocks for each function.

3.4.1. To balance a power grid with a large share of intermittent renewable generation

Participants reported that the key pre-requisites were the *flexible use of assets* in terms of grid operation, network connection sharing, accurate network models, and network visibility. A significant amount of demand-side response and demand-side balancing was thought to be required; notably, customer participation was considered important. Three techniques were cited as equally important crucial steps: accurate generation forecasting (volume and location), ICT to deliver real-time data, and alterations to the current regulatory framework. Together, these accounted for 59% of all responses.

3.4.2. To increase observability and controllability of the power grid

There was strong agreement amongst the participants that the critical step was to *install appropriate equipment* across all levels of the transmission and distribution networks. In particular, metering in distribution networks, and phasor measurement units in both transmission and (some) distribution networks. In the UK context, the use of smart meters (residential or commercial premises) for this purpose is not yet relevant, but in a different regulatory framework, these too could contribute to this function. These two responses accounted for 54% of all responses. Participants commented that this function would need significant new investment and regulatory support for increased capital expenditure.

Table 4
The functions classified as essential (values indicate number of votes).

Item	Essential	Desirable	Not important	No opinion
To balance a power grid with a large share of intermittent renewable generation	63	14	0	0
To increase observability and controllability of the power grid.	58	18	0	1
To enable deployment of demand side response technologies	57	18	0	1
To enable active network management	56	19	0	2
To allow integration of active loads (e.g. electric vehicles, heat pumps).	55	22	0	0

3.4.3. To enable deployment of demand-side response (DSR) technologies

Tariffs to incentivise DSR were considered as the most important step, plus understanding customer behaviour with differing pricing points. This is coupled with the second item, smart meters, which some participants said should have the capability to operate with dynamic tariffs. The third item summarised changes to the relevant regulatory/commercial frameworks that were considered to be needed to enable DNOs to deploy DSR as an alternative to network investment (or additional generation), and to allow DSR to participate in the balancing services market. Suggestions for such changes occurred at several points in both rounds of our consultation, and may signify that the current regulatory system does not satisfy the needs of the electricity system, or the widely anticipated benefits from RIIO mechanisms. The three most highly ranked items accounted for 69% of all responses.

3.4.4. To enable active network management

Participants concurred that *deploying monitoring and control equipment* (including communications) was the critical step (a third of all responses). However, structural barriers were identified, such as clarifying the split of responsibilities between DNOs and the TSO. Together these responses amounted to 60% of the total.

3.4.5. To allow integration of active loads (e.g. electric vehicles, heat pumps)

The principal step was *managing pricing and costs* relating to both the supply and demand sides. For example, participants raised the need for clear rules on connection charges, and for incentive programmes (with variable pricing) to support management of active loads. Three items were then cited as equally important: consumer engagement, DSR, and monitoring of the low voltage network. In a similar fashion to the function to enable DSR, consumer engagement needs better understanding of what incentives will encourage consumers to participate in active management and load limiting. Notably, for both functions, issues such as encouraging the use of efficient appliances or energy conservation did not feature highly as a pre-requisite for the integration of active loads. These responses accounted for 46% of all responses.

3.4.6. To integrate energy storage

Although considered as an essential function that SGs should be able to deliver, energy storage was generally treated by participants as an immature solution or an *alternative* to SGs. The most cited critical steps were the *improvements in technical solutions* and *regulatory change* (removing the barriers to investment), and clarity about business models (totalling 56% of responses). As a parallel solution to SGs, one participant considered that storage would be unnecessary if the other essential functions fulfilled their potential. Another participant commented in round 1 of our survey that given enough storage, the grid will not need to be smarter than it is currently. A third participant argued that increasing the storage of the present grid, would increase its smartness, even if other 'smart' functions were not implemented.

Table 5
Summary of the ranked responses relevant to the perceived critical steps to implement new SG functions. The full listing for each function is given in Appendix B, Tables B.4a – B.4f.

	Rank	Votes (#)	Votes (%)
To balance a power grid with a large share of intermittent renewable generation (Table B.4a)			
Flexible use of all assets	1	7	17%
Demand-side reduction/balancing	2	5	12%
Accurate generation forecasts	3=	4	10%
Fast/reliable ICT for real-time data	3=	4	10%
New or clear regulation	3=	4	10%
To increase observability and controlability of the power grid (Table B.4b)			
Installation of monitoring and control equipment	1	14	38%
Roll-out of smart meters	2	6	16%
Increased investment	3=	4	11%
Real-time data and fast communications	3=	4	11%
To enable deployment of DSR technologies (Table B.4c)			
New tariff structures	1	9	22%
Smart meters	2	7	17%
Improved customer information/acceptance	3=	6	15%
Change in the regulatory/commercial frameworks	3=	6	15%
To enable active network management (Table B.4d)			
Deploying monitoring, metering, and control technologies	1	11	33%
Solve the Supplier-DNO-TSO boundaries and responsibilities	2	5	15%
Change the regulatory/commercial frameworks	3	4	12%
To integrate active loads (Table B.4e)			
Pricing and costs	1	5	13%
Consumer engagement	2=	4	11%
Demand-side response	2=	4	11%
Deploy local network monitoring	2=	4	11%
To integrate energy storage (Table B.4f)			
Improved and affordable technical solutions	1	9	24%
Regulatory reform to accommodate storage	2=	6	16%
Clarify or devise types of business case/model	2=	6	16%

3.5. Implementation mechanisms

We investigated how likely the SG functions identified were to be implemented and whether they were likely to develop in rural or urban areas. On a scale of −5 (very unlikely to be implemented) to +5 (very likely to be implemented) all functions received positive scores, indicating a limited to moderate expectation that these functions will materialise (Fig. 2). The functions which participants most expected to be implemented were observability and controllability of the grid, and the integration of active loads. Facilitating energy storage received the lowest likelihood ratings reflecting the immaturity of the technology, its regulation, and uncertainty of the business model. Four of the six functions – balancing renewables, increasing observability and controllability of the grid, active network management and storage integration - were expected to be implemented incrementally either through trials or deployed in parts of the network in critical need. In contrast, the deployment of DSR technologies was expected to be implemented by roll-out, with local trials as a second option. Integration of active loads was expected to occur incrementally via trials on an ad hoc basis. In terms of spatial variation, there was an expectation that virtually all functions would be more likely to be implemented in urban settings than in rural ones; this was particularly the case for DSR technologies, active load management, and controllability (Fig. 2).

4. General discussion and conclusions

A low-carbon and secure energy system will require smarter ways of producing, distributing and using electricity. This research provides a systematic in-depth exploration of private-, public- and third sector stakeholder views on SG development in the UK, on a scale and depth not previously undertaken. Our findings show that experts agree on the need to make electrical delivery smarter, and highlight a range of potential benefits resulting from SGs, including efficiencies, cost reductions, and network balancing. However, a variety of barriers and pitfalls for SGs were also identified, including in particular issues with incentivising investment, and the potential for customer disengagement. We have identified key functions of a future smart grid as well as the critical steps that must be taken to achieve each of these functions and a range of factors that are likely to impact the transition to a smarter grid. In doing so we provide insight into the types of technical, social and policy shifts that may be required to achieve a smarter grid.

In particular we identify key sociotechnical factors that are likely to impact on the transition to an increasingly smarter grid and the clarity of issues within each factor. Our stakeholders were quite consistent in opinion on issues relating to investment, technical issues and standards, highlighting the importance of policy stability to promote investment and reduce industry inertia, and the necessity of developing smart metering and data exchange standards, communication protocols and active network management. Interestingly, issues within customer engagement, coordination, regulation, market structure and data handling covered a much larger range of issues, indicating a wide range of opinion, and less agreement amongst our participants. These may indicate where future research is needed in order to develop understanding and clarity.

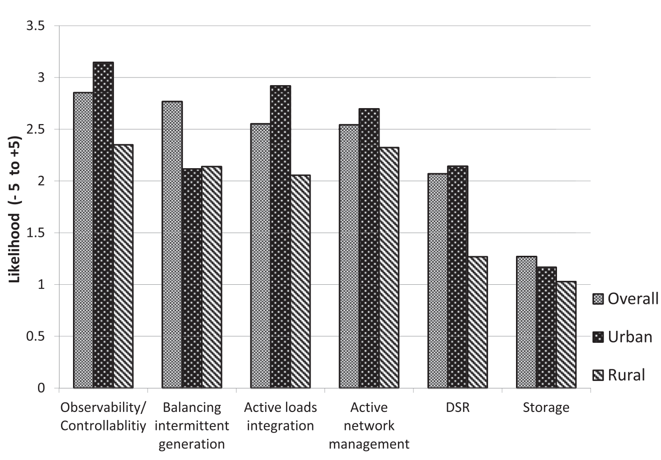

Fig. 2. Expected method likelihood of implementing each function in different geographical contexts (see text for full function titles).

Experts broadly agreed that key SG functions include:

- balancing a power grid with a large share of intermittent renewable generation;
- increasing observability and controllability of the power grid;
- enabling deployment of DSR technologies;
- enabling active network management;
- allowing integration of active loads (e.g. electric vehicles, heat pumps).

All were thought to be fairly likely to be implemented, mostly gradually being connected through trials or in parts of the network that are in critical need; and more likely in urban than rural settings. This would appear to be consistent with the Low Carbon Network Fund SG pilots currently being run.

Notably, costs appear to dominate both the expected benefits and pitfalls of SGs: expert participants expected SGs to deliver significant cost reductions via deferred investment, efficiency savings, or otherwise, provided that the costs of implementation and maintenance of the required technologies can be met; failure of the latter would fail to deliver the former. Environmental benefits also feature highly, reflecting the importance of climate change mitigation, together with energy security, on the UK government energy agenda. Social criteria – particularly, but not limited to, consumer engagement – feature more prominently as potential barriers than benefits, suggesting significant steps need to be taken if the potential of SGs is to be realised for wider society, including vulnerable (e.g. fuel poor) consumers. Similarly, since stakeholders felt many smart energy system functions are more likely to be implemented in urban areas, compounding current physical, socio-structural and infrastructural differences, there is a need for a better understanding of the two-way relationship between these inequalities and the uptake of various smart services and technologies [see also 53].

Our findings highlight that consumer buy-in will be essential for SG roll-out. Early experiences with smart meters will be formative for subsequent DSM and SG implementation. Experts felt that consumer trust will in part be reliant on assurances that data protection and privacy measures are sufficient, along with increased transparency and benefit-sharing since the current public perception is that energy companies do not act in consumers' best interest. Data protection and privacy were clearly identified as a problematic aspect, inherent to smarter girds, where much greater transparency on how, where and when energy is used will be essential. Associated reassurances and data protection safeguards should be devised and implemented to increase customer trust – expanding beyond domestic customers to larger business and industrial demand. Additionally, predictable and sustained policy support will be critical to ensure requisite investment and innovation for SGs, including the emergence of new market entrants.

The goal of this work was to investigate the stakeholder perspectives of SG development for the UK. Using robust stakeholder elicitation methods we produced an interdisciplinary examination of the key factors affecting the smartening of UK's electricity grid. We paid particular attention to behavioural issues and spatial dynamics yielding representative stakeholder views on energy system change. Our study revealed the possibilities and nature of future SGs along with the processes by which the transition may be achieved. The observations made in the context of the UK will have applicability to well-developed electricity systems with deregulated market structures in other nations. Although the details of, for example, regulatory frameworks may differ, many of the companies owning and operating networks are multinational in nature.

Future work could seek to capture the views of comparable experts in other countries to give insight into how SGs are evolving globally. Nevertheless, our unique study captured the views of an audience key to the SG decision-making process and representative of the sector.

Authors' note

The authors declare no conflicts of interest.

Acknowledgements

This research was undertaken as part of the research programme of the UK Energy Research Centre, supported by the UK Research Councils under Natural Environment Research Council award NE/J005975/1. The funder had no involvement in study design, data collection and analysis, or writing up this paper. We would like to thank Sophie Poulain for her help with data management.

Appendix A. Survey questions

A.1 Policy Delphi round 1

Participants were asked to provide their views on the following areas:

(i) Benefits and pitfalls:
a. “Please identify up to three key benefits of smarter grids”
b. “Please identify up to three key pitfalls of smarter grids”
(ii) Functions of smarter grids: “Please rate the following list of potential functionalities as Essential, Desirable, Not important, No opinion according to the buttons provided. You can add up to 2 functions which you consider essential for a smart grid, but are missing from this list.”
i. To enable two way communication with assets (substations, transformers) for condition monitoring.
ii. To increase observability and controllability of the power grid.
iii. To enable automated fault identification.
iv. To implement self-healing capabilities
v. To enable flexible time of use tariffs
vi. To enable deployment of demand side response technologies
vii. To enable aggregation of distributed energy resources
viii. To enable aggregation as a market service
ix. To enable active network management
x. To allow integration of active loads (e.g. electric vehicles, heat pumps).
xi. To enable data use for near to real time network operation.
xii. To incentivise co-operation by utilities to provide best fit solutions for grid management
xiii. To minimise the cost of upgrading electricity networks to 2050.
xiv. To protect vulnerable consumers from price increases
xv. To ensure system cost benefits are passed to the consumer
xvi. To provide a wider variety of customer services
xvii. To facilitate new market entrants. (This might include aggregators, energy service providers,generators, etc)
xviii. To enable real time information flow between TSO and DNO
xix. To balance a power grid with a large share of intermittent renewable generation
xx. To enable fuel shifting between gas, electricity and heat
xxi. To enable load shedding and shifting at all voltage levels

Please feel free to add up to 2 functions which you consider essential for a smart grid, but are missing from the previous list.

(iii) factors facilitating or impeding the development of smarter grids:
a. Please think about how the following factors may facilitate or impede the process of making electricity grids smarter:
i. Standards: What three key areas of standardisation do you think will have the greatest significance for making electricity grids smarter?
ii. Technical issues: What three key technical areas do you think will have the greatest significance for making electricity grids smarter?
iii. Data Handling (incl. cyber security): What three key issues relevant to data handling do you think will have the greatest significance for making electricity grids smarter?
iv. Structural: What three key structural areas (referring to the structure of the UK Energy Market Industry) do you think will have the greatest significance for making electricity grids smarter?
v. Regulation: What three key issues relevant to regulation do you think will have the greatest significance for making electricity grids smarter?
vi. Coordination: What three key issues relevant to coordination between DECC and Ofgem do you think will have the greatest significance for making electricity grids smarter?
vii. Customer engagement: What three key issues relevant to customer engagement do you think will have the greatest significance for making electricity grids smarter?
viii. Investment: What three key issues relevant to attraction of investment do you think will have the greatest significance for making electricity grids smarter?
ix. Other factors: Briefly identify up to two key drivers and barriers to the process of smartening the grid –that is issues, events, trends or actors which in your opinion could facilitate or impede the process of making electricity grids smarter.

A.2. Policy Delphi round 2

Participants were asked to provide their views on the following areas:

(i) “To be able to implement function (X-where X corresponds to functions 1–6) the detailed critical steps are: …”
1) To balance a power grid with a large share of intermittent renewable generation.
2) To increase observability and controllability of the power grid.
3) To enable deployment of demand side response technologies.
4) To enable active network management.
5) To allow integration of active loads (e.g. electric vehicles, heat pumps).
6) To facilitate energy storage.
(ii) In a scale from −5 (very unlikely) + 5 (very likely) please indicate:
a. How likely, in general, do you think it is for this function to be implemented?
b. Specifically for URBAN areas, how likely do you think it is for this function to be implemented?
c. Specifically for RURAL areas, how likely do you think it is for this function to be implemented?
(iii) How is this function likely to be implemented?
a. Through trials gradually being connected together over time
b. By a mandated roll-out
c. In parts of the network in critical need only
d. Through gradual asset replacement
e. In an ad-hoc uncoordinated fashion By some combination of the above (please explain)
f. Other

Appendix B. Data tables

Table B.1a
Perceived expected **benefits** from smarter grids.

Perceived or expected benefit	Rank	Votes (#)	Votes (%)
Efficiency/loss reduction	1	32	15%
Cost reduction	2	31	14%
Enable active network management	3	21	10%
Facilitation of more renewables	4=	18	8%
Emissions reduction	4=	18	8%

(*continued on next page*)

Table B.1a (*continued*)

Perceived or expected benefit	Rank	Votes (#)	Votes (%)
Better balancing	6=	16	7%
Demand reduction/management	6=	16	7%
Consumer information/value	6=	16	7%
Community/consumer engagement	9	14	7%
Decentralised generation	10	10	5%
Facilitate EVs and heat	11	8	4%
Other [a]	–	14	6%
Totals	–	200	100%

[a] Single opinions or answers which could not be categorised.

Table B.1b
Perceived expected **pitfalls** from smarter grids.

Perceived or expected pitfall	Rank	Votes (#)	Votes (%)
Investment issues	1	30	15%
Complexity of proposed solutions	2	24	12%
Disengaged/uncooperative customers and stakeholders	3	21	11%
Data protection/privacy concerns	4	14	7%
Customer worse off	5	12	6%
Unproven/underdeveloped technology	6=	10	5%
Disjointed decision making/planning/system fragmentation	6=	10	5%
Business case unclear/not fit for purpose	8	8	4%
System vulnerability/less resilience	9=	7	4%
Poor/slow implementation	9=	7	4%
Conflict of interests (utilities)	9=	7	4%
Over-expectation/overpromising	12=	6	3%
Poor definition/understanding	12=	6	3%
High data volume	14=	5	3%
Regulatory constraints	14=	5	3%
Other[a]	–	28	16%
Totals	–	214	100%

[a] Single opinions or answers which could not be categorised.

Table B.2a
Perceived **drivers** for smarter grids.

Perceived driver	Rank	Votes (#)	Votes (%)
Increase renewables integration	1	12	12%
Clear Government policy and leadership	2	10	10%
High uptake of PV, EV, and heat pumps	3	8	8%
Low carbon technologies	4	7	7%
Customer benefits/engagement	5=	6	6%
Distributed generation	5=	6	6%
Climate change and emissions reduction	5=	6	6%
Right regulatory framework	8	5	5%
Demand increase	9=	4	4%
Financial incentives	9=	4	4%
Pricing	9=	4	4%
Supply security	9=	4	4%
Cost cutting and efficiency	9=	4	4%
Infrastructure investment	9=	4	4%
Rising prices/costs	15=	3	3%
Demand management/reduction	15=	3	3%
EU policy implementation	15=	3	3%
Customer pull	18=	2	2%
Suppliers cooperation	18=	2	2%
Other [a]	–	4	4%
Totals	–	101	100%

[a] Single opinions or answers which could not be categorised.

Table B.2b
Perceived **barriers** to smarter grids.

Perceived barrier	Rank	Votes (#)	Votes (%)
Customer disengagement/resistance	1	22	25%
Unclear policy, governance, and changing targets	2	17	19%
Industry inertia and resistance	3=	11	13%
Investment and costs	3=	11	13%
Complexity of solutions	4=	3	3%
Data protection/privacy	4=	3	3%
Lack of expertise/innovation capacity	4=	3	3%
UK market structure	4=	3	3%
Future uncertainties	8	5	6%
Infrastructure needs	9=	2	2%
Lack of innovation	9=	2	2%
Other [a]	–	6	6%
Totals	–	88	100%

[a] Single opinions or answers which could not be categorised.

Table B.3a
The ranked responses relevant to standards that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Smart metering	1	14	24%
Communication protocols	2=	12	21%
Device/appliance data exchange and controls	2=	12	21%
Consistency of approaches to long-term planning	4	4	7%
Demand management	5=	2	3%
Utility/industry collaboration	5=	2	3%
Other[a]	–	12	24%
Totals	–	58	100%

[a] Single opinions or answers which could not be categorised.

Table B.3b
The ranked responses relevant to technical issues that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Communications	1	16	28%
Active network management	2	13	23%
Condition and voltage monitoring	3	7	12%
ICT and data management/storage	4	6	11%
EV facilitation	5=	3	5%
Smart metering	5=	3	5%
Interoperability	7	2	4%
Other[a]	–	7	14%
Totals	–	58	100%

[a] Single opinions or answers which could not be categorised.

Table B.3c
The ranked responses relevant to data handling that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Data protection/security	1	13	21%
Privacy guarantees	2	8	13%
Public acceptability/trust	3	6	10%
Real-time data	4=	5	8%
Standardisation	4=	5	8%
ICT hardware	6	4	6%
Cyber security	7=	3	5%
Data management location	7=	3	5%
Data volume	7=	3	5%
Market transparency	7=	3	5%
Interoperability	11=	2	3%
Data integrity	11=	2	3%
Other [a]	–	6	12%
Totals	–	63	100%

[a] Single opinions or answers which could not be categorised.

Table B.3d
The ranked responses relevant to market structure, that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Lack of cooperation between DNOs and suppliers	1=	7	13%
Sector fragmentation	1=	7	13%
Government intervention to enforce changes	3=	3	5%
Development of demand/storage/EV/heat markets	3=	3	5%
Pricing structures	3=	3	5%
Regulation to encourage DNO participation	3=	3	5%
Aggregator opportunities	7=	2	4%
DNO-customer relationships	7=	2	4%
Incumbents rigidity	7=	2	4%
Policy makers	7=	2	4%
Poor balancing	7=	2	4%
Pricing/tariff clarity	7=	2	4%
Settlements structure change	7=	2	4%
Small generators access	7=	2	4%
Subsidise renewables and communication R&D	7=	2	4%
Other[a]	–	12	24%
Totals	–	56	100%

[a] Single opinions or answers which could not be categorised.

Table B.3e
The ranked responses relevant to regulation, that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Effective commercial arrangements and pricing	1	11	20%
Transform DNO structure/operation	2	10	18%
Incentivise cooperation and alternative revenues	3	5	9%
Provide early guidance on investment	4	4	7%
Data access/availability	5=	3	5%
Facilitate smart metering	5=	3	5%
Strong regulator	5=	3	5%
1/2 hourly settlement	8=	2	4%
Allow more aggregation	8=	2	4%
Standardisation	8=	2	4%
Other[a]	–	10	20%
Totals	–	55	100%

[a] Single opinions or answers which could not be categorised.

Table B.3f
The ranked responses relevant to co-ordination that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Smart metering	1=	5	11%
Align goals and objectives	1=	5	11%
Align incentives with objectives	1=	5	11%
Consistent messages/approaches	4=	4	9%
Long term vision/commitment	4=	4	9%
Broaden scope/vision	6=	3	7%
Funding availability	6=	3	7%
Better communication	8=	2	4%
Broaden skills base	8=	2	4%
Clarify decarbonisation targets	8=	2	4%
Future scenarios agreement	8=	2	4%
Build consumer choice and trust	8=	2	4%
Other[a]	–	7	14%
Totals	–	46	100%

[a] Single opinions or answers which could not be categorised.

Table B.3g
The ranked responses relevant to customer engagement that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Customer and public education/awareness	1	25	39%
Customer willingness to comply/share data/shift demand	2	14	22%
Pricing	3	5	8%
Provide tailored solutions	4=	4	6%
Smart meter functionality	4=	4	6%
Billing info clarity	6	3	5%
Savings/cost reduction	7	2	3%
Other[a]	–	7	14%
Totals	–	64	100%

[a] Single opinions or answers which could not be categorised.

Table B.3h
The ranked responses relevant to investment that are expected to significantly influence SG development.

	Rank	Votes (#)	Votes (%)
Long-term regulation/policy certainty/objectives	1	18	36%
Uncertain ROI	2	9	18%
New modes of financing/business models	3=	4	8%
New value delivery mechanisms (e.g. flexibility)	3=	4	8%
Future uncertainties	5	3	6%
Customer benefit clarity	6=	2	4%
Demand side investment policy	6=	2	4%
Ensure wide participation	6=	2	4%
High investment costs	6=	2	4%
Upgrade/maximise system assets performance	6=	2	4%
Other[a]	–	2	4%
Totals	–	50	100%

[a] Single opinions or answers which could not be categorised.

Table B.3i
The functions classified as essential, desirable, and not important.

Item	Essential	Desirable	Not important	No opinion	Cluster
To balance a power grid with a large share of intermittent renewable generation	63	14	0	0	Essential functions
To increase observability and controllability of the power grid.	58	18	0	1	
To enable deployment of demand side response technologies	57	18	0	1	
To enable active network management	56	19	0	2	
To allow integration of active loads (e.g. electric vehicles, heat pumps).	55	22	0	0	
To minimise the cost of upgrading electricity networks to 2050.	45	24	4	4	Desirable functions
To enable flexible time of use tariffs	42	32	2	1	
To enable aggregation of distributed energy resources	40	31	4	2	
To enable two-way communication with assets for condition monitoring.	38	34	1	4	
To enable data use for near to real time network operation.	37	36	0	4	
To enable automated fault identification.	29	47	0	1	

(continued on next page)

Table B.3i (*continued*)

Item	Essential	Desirable	Not important	No opinion	Cluster
To enable real time information flow between TSO and DNO	27	36	6	8	Least important functions
To enable load shedding and shifting at all voltage levels	26	44	1	6	
To ensure system cost benefits are passed to the consumer	23	39	8	7	
To enable fuel shifting between gas, electricity and heat	19	42	8	8	
To protect vulnerable consumers from price increases	18	45	8	6	
To incentivise co-operation by utilities to provide best fit solutions for grid management	16	40	11	10	
To facilitate new market entrants.	16	46	11	4	
To enable aggregation as a market service	13	47	10	7	
To implement self-healing capabilities	12	56	4	5	
To provide a wider variety of customer services	8	44	21	2	

Table B.4a
The ranked responses relevant to the perceived critical step to implement SG function: balancing a power grid with a large share of intermittent renewable generation using new ‘smart’ techniques and technologies.

	Rank	Votes (#)	Votes (%)
Flexible use of all assets	1	7	17%
Demand-side reduction/balancing	2	5	12%
Accurate generation forecasts	3=	4	10%
Fast/reliable ICT for real-time data	3=	4	10%
New or clear regulation	3=	4	10%
Customer participation/acceptance	6=	3	7%
Understand efficient balancing	6=	3	7%
Technology development	8	2	5%
Other[a]	–	9	18%
Totals	–	41	100%

[a] Single opinions or answers which could not be categorised.

Table B.4b
The ranked responses relevant to the perceived critical step to implement SG function: increased controllability and observability of the power grid.

	Rank	Votes (#)	Votes (%)
Installation of monitoring and control equipment	1	14	38%
Roll-out of smart meters	2	6	16%
Increased investment	3=	4	11%
Real-time data and fast communications	3=	4	11%
Automation of control	5=	2	5%
Clear roles and responsibilities	5=	2	5%
Other[a]	–	5	15%
Totals	–	37	100%

[a] Single opinions or answers which could not be categorised.

Table B.4c
The ranked responses relevant to the perceived critical step to implement SG function: deployment of demand-side response technologies.

	Rank	Votes (#)	Votes (%)
New tariff structures	1	9	22%
Smart meters	2	7	17%
Improved customer information/acceptance	3=	6	15%
Change in the regulatory/commercial frameworks	3=	6	15%
Technology development and trials	5=	2	5%
New business models for DSR and market participants	5=	2	5%
Adoption of controllable demand	5=	2	5%
Better understanding of demand-side issues	5=	2	5%
Other[a]	–	5	10%
Totals	–	41	100%

[a] Single opinions or answers which could not be categorised.

Table B.4d
The ranked responses relevant to the perceived critical step to implement SG function: active network management.

	Rank	Votes (#)	Votes (%)
Deploying monitoring, metering, and control technologies	1	11	33%
Solve the Supplier-DNO-TSO boundaries and responsibilities	2	5	15%
Change the regulatory/commercial frameworks	3	4	12%
Change the regulatory/commercial framework	4	3	9%
Active network management is already here	5=	2	6%
Fund relevant innovation and incentivise investment	5=	2	6%
Understand the problem at hand	5=	2	6%
Other[a]	–	4	12%
Totals	–	33	100%

[a] Single opinions or answers which could not be categorised.

Table B.4e
The ranked responses relevant to the perceived critical step to implement SG function: integrate active loads (e.g. electric vehicles, heat pumps).

	Rank	Votes (#)	Votes (%)
Pricing and costs	1	5	13%
Consumer engagement	2=	4	11%
Demand-side response	2=	4	11%
Deploy local network monitoring	2=	4	11%
Standardisation of interfaces/operation	5=	3	8%
Deployment of active network management	5=	3	8%
Smart metering	5=	3	8%
Technology development	5=	3	8%
Need more research/trials	9=	2	5%
Stimulate technology adoption	9=	2	5%
Other[a]	–	5	15%
Totals	–	38	100%

[a] Single opinions or answers which could not be categorised.

Table B.4f
The ranked responses relevant to the perceived critical step to implement SG function: integrate energy storage.

	Rank	Votes (#)	Votes (%)
Improved and affordable technical solutions	1	9	24%
Regulatory reform to accommodate storage	2=	6	16%
Clarify or devise types of business case/model	2=	6	16%
Investment Issues	4	5	14%
Decide which technology to deploy	5	3	8%
Other[a]	–	8	24%
Totals	–	37	100%

[a] Single opinions or answers which could not be categorised.

Appendix C. Analysis of participant bias

From the original list of experts contacted, the respondents were self-selecting. We examined the smart grid function responses for bias. The small sample size limits the analysis of sub-groups that can be conducted. For chi-square analysis, it is necessary to have expected counts of at least of five in each response category within each sub-group). For level of expertise and background, participants are spread across too many sub-groups that each contains only a few respondents. Chi-square analysis, however, can viably be conducted on gender and sector, provided in the case of the latter that 'economics' ($N = 2$) is recoded into 'other' ($N = 10$) to make a sub-group comprising 12 respondents.

The analysis shows that only one function response varied by gender, and one response varied by sector. The item 'To enable aggregation of distributed energy resources' was significantly more likely to be seen as essential by female respondents, while male respondents were more likely to see this function as only desirable or unimportant (see Table C.1). In respect of the function 'To protect vulnerable consumers from price increases', social scientists and engineers were significantly more likely to see this as essential than business or 'other' sector respondents, who tended to see it as only desirable or unimportant (see Table C.2).

Table C.1
Gender differences in responses to the smart grid function 'To enable aggregation of distributed energy resources' (columns show N and %).

Rating	Male ($N = 47$)	Female ($N = 18$)	Total ($N = 65$)	X^2 (p)	Cramer's V
Essential	18 38.3%	14 77.8%	32 49.2%	8.66 (0.034)	0.37
Desirable	23 48.9%	4 22.2%	27 41.5%		
Not important	4 8.5%	0 0.0%	4 6.2%		
No opinion	2 4.3%	0 0.0%	2 3.1%		

Table C.2
Sector differences in responses to functionality 'To protect vulnerable consumers from price increases' (columns show N and %).

	Business	Engineer	Social Science	Other	Total	X^2 (p)	Cramer's V
Essential	0 0.0%	9 39.1%	5 41.7%	1 8.3%	15 23.1%	17.09 (0.047)	0.30
Desirable	14 77.8%	10 43.5%	4 33.3%	8 66.7%	36 55.4%		
Not important	2 11.1%	2 8.7%	1 8.3%	3 25.0%	8 12.3%		
No opinion	2 11.1%	2 8.7%	2 16.7%	0 0.0%	6 9.2%		

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UK smart grid development: an expert assessment of the benefits, pitfalls and functions

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2015-03-27

Xenias D, Axon CJ, Whitmarsh L, et al., (2015) UK smart grid development: an expert assessment of the benefits, pitfalls and functions. Renewable Energy, Volume 81, September 2015, pp. 89-102

https://doi.org/10.1016/j.renene.2015.03.016