FAR out? An examination of converging, diverging and intersecting smart grid futures in the United Kingdom

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1. Introduction

Scenarios enable organisation and translation of economic, technological, competitive, political, and societal information into a framework [1] to uncover possible alternative futures, challenge dominant worldviews [2] and inform decision-making. They are widely used for business planning, devising military strategy, or to inform policy development [3]. Developments of the techniques in recent years have made the scenario planning process faster and more efficient [4]. However, Chermack and Coons [4] recognise that this has led to disappointing results, whilst others warn of the need to check for underlying biases [5] or a lack of variation [6]. One particular scenario building method is field anomaly relaxation (FAR) which aims to create a set of internally consistent futures for policy formulation and decision-making purposes [7–10]. By building on Lewin's social field theory, Zwicky's morphological approach and the relaxation methods of engineering, FAR is a 'whole-pattern futures projection' method [9]. FAR provides a structured and transparent approach for systematic thinking through a highly ordered series of events. It is a variant of morphological analysis [11,12] and underwent refinement [13–16], followed by extensions for different types of problems: replacing the tree-structure of scenario development with a network allowing for a game-theoretic approach [17,18], hybridisation with soft-systems methodology [19], and the use of mathematical methods to discover maximally diverse scenarios [20]. FAR has been used in a wide variety of application domains, for example business-related planning [21–23], food security [20], military planning [24,25], policy development [26], and the future development of text mining [27].

With many technological and non-technological options that may change the way society generates, delivers and consumes energy, smart grids (SG) are seen as the silver bullet of cost-effective, reliable and low carbon energy systems. The development of SGs is a socio-technical process [28], constructed incrementally as the outcome of multifaceted interactions across technologies, social, financial and governmental interventions [29]. While some aspects of SGs have been included in wider electricity network scenarios to date [30–32], they are limited in addressing the complexity of SG development. This is because the development of SGs goes beyond the electricity industry, interacting fundamentally with Information and Communication Technology (ICT) and transport sectors [33], and dependent on other socio-technical factors. Social factors include consumer concerns about data privacy/security and loss of control due to remote operation of appliances to manage peak load [34]. Market related factors include the development of pricing mechanisms and transition access management through regulation [35] and the provision of market and regulatory systems that will drive innovation and make innovation and investment in new services and technologies viable [36]. Financial and business related factors include the tensions between firms' seeking to gain competitive advantage [37–39] and the public good nature of some smart grid technologies [40] in a deregulated electricity industry; as well as the need to leverage enhanced rates of financing to support this new infrastructure while achieving a fair distribution of costs [41,42]. These factors are interdependent such that any choices made in any of these areas will influence the choices available in other domains. Consequently, any SG scenarios recognising their socio-technical nature need to consider these multi-dimensional factors, their interactions, and key transition points – rather than mere end points. This paper addresses this gap by employing and augmenting the FAR method. In principle this method can accommodate any number of factors, though the practical upper limited is suggested as seven [9]. Each factor can have alternative states (e.g., high vs. low) to be interrogated to form possible future states. Then these states are checked for their consistency [43] and surviving ones are formed into a string of events in a tree-like diagram starting from the present point to the future.

Yet, to date there is no detailed account of how FAR can be used to analyse SG futures, even though their application to engineering design, scenario development, policy analysis and innovation, with limited detail account of the method, was noted [44]. Using the UK as a case study, this paper addresses this gap by providing a detailed account of the development and application of an augmented FAR to produce scenarios for the development of smart grids in the UK. The objectives of this paper are three-fold: i) to provide a methodological account of our augmenting of FAR to incorporate expert feedback in developing UK smart grid scenarios; ii) to demonstrate how this method can be used to develop 'scenario pathways' dynamically rather than mere end points and iii) to identify areas that may be overlooked in the implementation of FAR, despite its intentions to become 'totality research' [45, p.30] and pursuit of an ambitious research programme involving a multidisciplinary research team.

The next section provides a background to the research in terms of the definition of smart grids, a review of SG-related scenarios, and their strengths and weaknesses in addressing SG development. Section 3 presents FAR methodology in-depth as presented in the literature. Section 4 discusses our extension to FAR and 5 offers a discussion of our findings. Section 6 is devoted to conclusions.

2. Smart grids as a wicked problem

The considerable variation in the definition of SGs across working groups and countries [46] is due to different functions and services that a smart grid may support – the term is somewhat misleading since it suggests an endpoint rather than a comparative state which is merely smarter than the current system. A broad and commonly-used definition comes from the Smart Grids European Technology Platform, suggesting that SGs are '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, economical and secure electricity supplies' [47].

Rather than a technology *per se*, SGs are an application (or group of applications) that better integrates different parts of the system: the supply mix; the technology and infrastructure characteristics of the system; data (availability, access and type); the regulatory and market frameworks; policy incentives and their effectiveness; consumer capability and willingness to engage. Various functions might be enabled or disabled in different markets as a result of interactions between these factors. For example, degrees of smart meter functionality will play a role, as will data access. To expand on this, if identical smart meters are installed in two different markets and in one of these markets, DNO access to real time smart meter data is limited to aggregated data for a street or with a time delay, then they will have limited insights compared to a DNO with better access, be it less aggregated data or less time-delayed access to data. The former is likely to have less knowledge about what low carbon technologies are installed and less ability to influence and manage demands from the grid. Their options for responsiveness, and for network management are thus more limited. Essentially, either of these differences (or many others) might emerge for technical or regulatory or social reasons, but the result would be less options for smartness on one system compared to the other. We argue that SGs are better identified in terms of functions and services that they can enable [48], and identify five essential functions in the UK context:

- Balancing a power grid with high volumes of variable renewable electricity generation.
- Increasing observability and controllability of the power grid. Observability is achieved by increasing sensor deployment (including smart meters) allowing DNOs and/or others have greater insight into the operational demands of the networks. Controllability (limited by observability) is achieved by deploying ICT and data management / mining technologies.
- Enabling deployment of demand-side reduction (DSR) technologies, that is reductions in demand or in peak demand on the customer side of the meter. It is expected that increased volumes of intermittent renewables will require DSR for balancing.
- Enabling active network management (ANM) as an alternative to the historical paradigm of passive network operation. ANM techniques allow for differentiated levels of smartness where appropriate across a network.
- Allowing the integration of active loads by deploying ANM to balance networks. Different ANM strategies exploit various aspects of observability and controlability.

These informed how we considered outcomes to be more or less smart. This focus does not rule out the possibility of other functions emerging which might be more useful or even as essential in other territories, since the starting point for selection might be different. These functions might yield benefits such as more effective integration of distributed production and higher and more volatile consumption, with new ICT approaches acting as a key enabler of many of these options. The role of DSR, via automated processes or active participation [49], is seen by many experts as key to enabling considerable volumes of system flexibility. Yet, there is substantial concern that this might not emerge due to a number of technical, economic and social capacities that end users need to possess [50] and associated social acceptability costs [51].

The mutual interdependencies across regulatory, organisational, policy, social, behavioural, and technical aspects make SGs an exemplary 'wicked problem'. According to Ritchey [52], wicked problems are '*those complex, ever changing societal and organisational planning problems that are difficult to define and structure properly because they won't keep still. They're messy, ambiguous and reactive, i.e., they fight back when you try to do something with them*'. Critically, wicked problems cannot be solved by only one perspective or discipline; but rather require an interdisciplinary approach that captures systemic interactions and interdependencies.

2.1 Review of smart grid scenarios

Only some elements of SGs have been covered in electricity/energy scenarios to date. In particular, there is a significant difference in the level of ICT integration envisioned within different scenarios, as well as how the future energy industry may be changed by the entrance of new stakeholders such as telecommunications companies and other actors currently seen as third parties. Focusing specifically on the UK, a selected list of energy scenarios and their coverage of specific SG aspects is summarised in **Table 1**. Ofgem's LENS Project [53] is a scenario study examining the UK electricity transmission and distribution networks, but does not discuss at length the future role that ICT may play within the system nor its implications for the energy market. Rather, it focuses on who would be the 'controlling' body of the electricity system, drawn from current stakeholders (distribution network operators, transmission operators, consumers etc.). DECC [54] and National Grid [55] also focus on generation and consumption technologies rather than ICT integration and the roles of other actors along the supply chain, including consumers. Elders et al. [31] briefly mention SG technology and ICT incorporation, but mostly examine the addition of renewable energy generation, discussing how the industry model may continue to be dominated by large, centralised actors, or might shift to microgrids and small-scale community generation. The Transition Pathway Project [56,57] only briefly mentions SGs as a tool for improving the efficiency of the system. To date, the role of ICT within different energy / electricity scenarios has been largely ignored.

Similarly, whilst a number of studies focus on the impact of technological advancement and economic growth on the future of SGs and the energy industry, most do not take into account the extent of the likely impact of policy changes and consumer behaviour. Where these issues are raised, they are often not discussed in detail. DECC's Pathway Analysis 2050 [58] does not attempt to include detailed policy or behavioural aspects. Ofgem's LENS Project [53] and the San Diego Smart Grid Study Final Report [59] include little detail about the level of public support for environmental or energy policies. These studies also provide minimal proposals for future government policies and regulations, usually only stating whether or not governments will be 'supportive' of a transition. Elders et al. [31] and Edison Electric Institute (EEI)'s workshop on USA SG scenarios [60] assume that consumer behaviour will act broadly in accordance with economic growth – i.e. when there is high economic growth then there will be a high public desire for sustainability policy and SG technology. Although there is some evidence that those on high incomes may be more interested in smart technologies [61], which are likely to command a price premium, a clear relationship between economic growth and SG adoption is by no way a given: societal norms, new functionalities or concerns (e.g., around data security) may outweigh economic drivers of technology diffusion. The EEI study [60] does, however, include a relatively detailed outline of government policies and regulations that may be instituted to accelerate the transition to a smarter grid. The Transition Pathways Project [56,57] recognises co-evolution of technology, institutions, business strategy, and user practices and considers small-scale individual actions as well as large-scale systemic shifts in the energy industry. Yet, likely impact of policy changes and consumer behavior, availability of capital, data privacy and security and how they might influence the emergence of different scenarios are overlooked.

The issue most overlooked by future energy scenarios is that of data privacy and security, and how consumers may react to the collection and use of their data by both public bodies and ICT companies. Types of data accessed, its latency and frequency are vital for the successful adoption and integration of SG technologies [48,62]. Objections to more sharing of personal information may lead to opposition to technology uptake, as has been demonstrated to be an issue in the Dutch case [63], and expressed amongst certain groups in the UK [64], and influence the nature and scope of smartness in a future power grid.

Table 1. Smart grid relevant aspects of energy scenarios[a]

		Technology											Government							Social/ Consumer Behaviour				Economy	
		SM*/ Data	ICT	CCS	Renewables	EVs	Appliances	D/T Networks**	Storage	Nuclear	Microgrid	DG***	Supply-side Support (R&D)	Demand-side support (incentives)	Regional/ National aspects	Regulations	Standards (interoperability)	Privacy	Security	Consumer Demand	Behaviour Shifts	New entrants	Added Services	Growth	Industry Structure
Elders et al. [31]	Focus on new energy generation technology and D/T network development, outline public and political behaviour as key parameters but don't expand on them in scenarios, just say whether political environment is 'liberal market-based' or 'interventionist', and whether public attitudes are weak/strong. No analysis of future co-evolution of parameters.	x	x	x	x	x	x	x	x	x	x	x	x/2							x			x	x	x
Ault et al. [53]	Focus on who would be the 'controlling' body of the system (D/T, consumer, etc.); no mention of smart meters; mentions changing business/industry model but only talks about current stakeholders, little mention of new entrants from other sectors. Attitudes and government role are drivers of scenarios, but no detail on policies, regulations, etc., not much about consumer attitudes and ICT implications for market.		x/2	x	x	x		x	x	x	x	x										x		x	x

DECC [58]	Focus on energy generation, not ICT integration into the system. Does not attempt to include policy or international context. Only about physical limits based on technology.			x	x	x	x	x		x		x								x				x	
NG [55]	Focus on energy demand and generation, specifically gas generation. Nothing about ICT and evolution of energy system.	x		x	x	x	x		x	x														x	
DECC [54]	Assessment of different demand and generation technologies to achieve least cost emissions reductions. Implicit assumptions of behaviour change with no consideration of ICT and new actors.			x	x	x	x		x	x										x	x			x	
Foxon et al. [57]	More explicit focus on governance patterns. Pathways based on co-evolution of tech, institutions, business strategy, and user practices. Trend based scenarios, but do account for 2050 UK 80% reduction goal as a catalyst for more emphasis on enviro policies.			x	x			x		x	x	x	x	x	x	x				x	x	x	x	x	x
Foxon [56]	Pathways focus on actors and governance in energy industry. Major players are government, business and consumers/ communities.	once		x	x	x	x/2	x		x	x	x	x	x		x				x	x	x	x	x	x
Pullins and Westerman [59]	Regional cost-benefit analysis of smart grids. Focus on SG impact on efficiency and dependability, and the tech that could be used to implement it, but don't talk about renewables integration, etc. focus on current grid, don't consider changing business model or new stakeholders. include time line and recommendations for implementation of SG system in SD.	x	x					x			x		x	x		x	x		x	x				x	

Berst [60]	Doesn't consider international pressure on social/ political context. Does emphasize that the market will expand with new stakeholders in ICT industry (Google, Wal-mart etc.)	x	x	x	x	x	x	x	x	x		x	x	x/2	State / federal jurisdiction	x	x		x	x	?	x	x	x	x
IEA [65]	Report on energy technologies with one chapter on SGs. Focus on technology and how SG implementation will reduce emissions. Provides prescriptions on what needs to be done but not who should do it/how. No emphasis on consumer reactions/ behaviour. No consideration of interaction of various factors.	x	x	x	x	x	x	x	x	x	x	x	x/2	x/2		x	x					x	x	x	x
IEA [66]	Based on BLUE map and Baseline scenarios, it talks about policy and industry changes that need to be made. More prescriptive analysis of current situation, less emphasis on scenario. Demand shifts are mentioned across OECD and China on very basic level.	x	x	x	x	x	x	x	x	x		x	x	x		x	x	x/2	x	x	x	x	x	x	x

[a] x/2 denotes ‘some’ coverage of the relevant aspect

* SM: Smart meters and data collection, ** Distribution/ Transmission Networks, *** Distributed Generation

2.2 The challenge for future socio-technical smart grid scenarios

Developing a comprehensive and usable set of SG scenarios requires attention to interdependencies between policy, organisational, market, business and regulatory systems, and the diverging perspectives of many different actors including consumers. The geographically divergent nature of low carbon energy systems [67,68] requires attention to spatial, along with temporal, aspects of electricity grids such that geographical heterogeneity and spatial clustering in SG development, associated urban-rural disparity [69] and dependencies on electric vehicle, smart home and other relevant local infrastructure [61] are taken into account. Furthermore, they should ideally capture uncertainties (e.g., wildcards) that may fundamentally (re-)shape the development of SGs.

Critically, and in contrast to previous scenarios in this field, new scenarios should capture broader systemic and cross-sectoral interactions representing not only the electricity industry and technical factors, but also the ICT, buildings and transport sectors and social, economic and political factors. The principal cross-sectoral interactions are: data access, consumer concerns about data privacy/security and loss of control of household devices due to remote operation to manage peak load [61,70,71]; development of dynamic pricing mechanisms and transition access management through regulation; provision of market and network regulatory systems to drive innovation and make innovation and investment in new services and technologies viable, and allow firms to seek competitive advantage (e.g., [37,38]; addressing the so-called broken value chain) in a deregulated electricity industry; as well as financing of infrastructure and achieving fair distribution of costs. This necessitates an in-depth, truly multidisciplinary approach that is consistent with the socio-technical transitions literature which describes how a particular cluster of technologies/services might evolve, diffuse and transform linked societal systems (energy-buildings-transport-ICT) and practices [e.g., 72,73]. These issues cannot be addressed through linear thinking [74]. These factors possess different types of uncertainties, dynamics and relative importance; capturing these in a simple twin-axis framework will not allow exploration of all plausible futures.

3. Method

A FAR approach is able to incorporate the multiple dimensions of a 'wicked problem' and interrogate their interactions. In this section we first describe the core FAR method, and then our developments to generate the augmented scheme.

3.1 The core FAR methodology

FAR involves a 4-step cycle that iterates between holistic ('wholes') composition and its constituents ('parts') and their interactions (Figure 1). This enables it '*to bring scattered information and insight together, allowing composition of a smaller set of alternatives from which internal inconsistencies have been removed*' [13, p.28]. FAR can be implemented in a cyclic mode by feeding scenarios developed in step 4 into step 1 in a second cycle. Yet, added effort may not be worthwhile if the first cycle produces internally consistent scenarios [43].

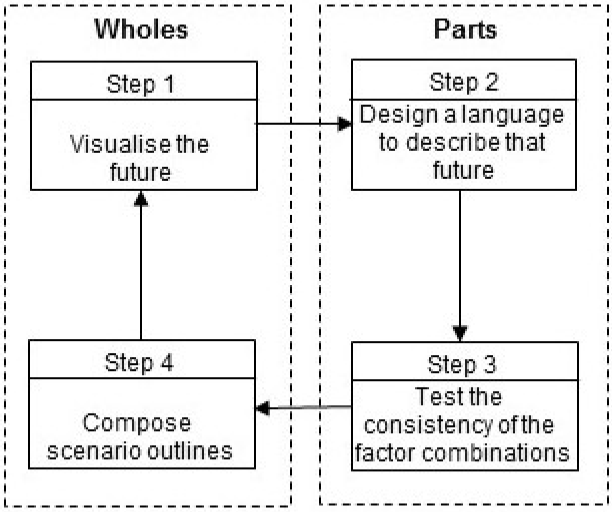

Figure 1. The original FAR method in four stages [9]

The four distinct steps of FAR are:

1. **Imagine alternative futures.** To incorporate a wide range of possible futures that can be shaped and refined as the process continues. The aim is to generate '*discussion and serious thought within the project team so that its members share a common set of images of future field prospects*' [9, p.337].

2. **Construct a symbolic language to describe the future.** To distinguish and bring together the many threads running through the visions of the future developed during step one, it is necessary to develop a '*a memorable acronym*' [43] that can be used to refer easily to individual configurations. This ought to be easy to grasp yet remain broad enough to describe the most significant characteristics of the visions of the future. These characteristics, so-called 'sectors', should not exceed seven due to the capacity of human memory. These should be mutually exclusive to avoid any overlap – it is partly the final scenarios' distinctness from one another that makes them interesting. Actual values each sector takes are called 'factors'. The sector/factor array ('morphological box') defines the problem space [75]. The arrangement of sectors and factors into an array (e.g. Table 3) allows for ready comparison between them and demonstrates how many configurations are possible.

3. **Relax the anomalies.** The objective is to reduce the number of possible configurations to a smaller number of internally consistent futures. Any given configuration is composed of factors numbering however many sectors have been used, and it is the relationships between *each pair* of factors that is the focus of the first part of step 3. Whilst Rhyne [7,9] proposed eliminating inconsistent pairs based on a broad question about plausibility, Coyle and Yong [15] put forward an approach more nuanced than a simple yes/no answer. This involves developing a matrix in which it is possible to grade the consistency of each factor against every other factor from another sector. Using a numerical scale, it is possible to gain insight into which configurations are more consistent than others. Rhyne's phrase '*relax the anomalies*', simply refers to the removal of any pairs that are deemed insufficiently

consistent or '*testing for consistency*[1]' [43]. The discourse to assess pairwise combinations leads to a '*transdisciplinary plane*' [9]. The second part of step 3 is to seek a '*gestalt appreciation*' [43] of whether the configuration, taken as a whole, has a consistency to it. This is because individual 'pairwise' consistency ratings do not ensure consistency *between* the pairs that together make up the configuration. Ritchey [76] identifies three types of inconsistencies to take into account: logical contradictions (driven from the nature of the concepts involved), empirical constraints (relationships not being plausible on empirical grounds), and normative constraints (due to ethical or political considerations). Of these, he suggests that normative consistency checking is saved to last so that all possible futures are explored, rather than only the desirable ones. Together the two parts of step 3 reduce the number of configurations by several orders of magnitude.

4. **Compose alternative scenarios.** The surviving configurations are then assembled to make scenarios – strings of configurations that together describe how the future unfolds. Coyle et al. (1994) build on Rhyne's method by merging similar configurations together into one cluster. We recount our own experiences of this below; however, the essential feature of step 4 is the creation of scenarios using the configurations that result from the previous step. This is done through a highly iterative process, taking place over several days to a week, where the central question is '*can we imagine a situation where this leads to that*?' This is, as Coyle and Yong [15, p.275] say, '*by far the most subjective part of FAR*', but the experiences of both Rhyne and Coyle (and, in the end, ourselves) were that familiarity with the symbolic language and clustered configurations results in a certain confidence in their ultimate ordering.

3.2 An augmented FAR methodology

A system as technically complex as SG requires development the FAR to be extended. Whilst we have done this in the context of SG, we suggest that other similarly complex problems share this need. The SG proposition is characterised by bottom-up technical development and deployment in a framework of strict regulation (technical and market), user engagement and government policy. User engagement to initiate demand-side response is essential for a cost-effective development of SGs [62]. The electrical power system (generation, transmission, distribution) is not free to develop in an unconstrained fashion. Any work to develop possible futures of SGs needs to incorporate the specialized technological power sector knowledge alongside regulation, policy, social aspects and business models. We therefore opted to formally incorporate expert elicitation in an augmented FAR (Figure 2).

[1] In earlier work, Coyle and Yong (1996) refer to 'coherence' rating.

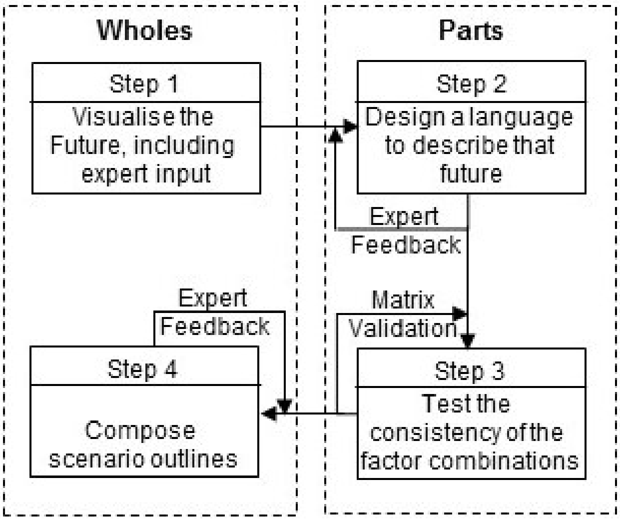

Figure 2. The augmented FAR method incorporating expert elicitation.

We describe five novel developments to the core FAR methodology (the details of implementation are explained in Section 4):

1. **Stakeholder engagement:** Rhyne [7] notes the benefits of intermittent involvement of decision-makers and analysts who may use the results (scenarios) in the process, but a full set of stakeholders is domain experts, decision-makers, analysts, and end-users. Expert stakeholder groups can provide domain knowledge, be a critical voice, checks results, and ensure transparency at each stage. Keeping stakeholders engaged at each stage ensures that scenarios are relevant for end-users.

2. **Multidisciplinary expertise:** As some technical systems (such as SG) developed from an already sophisticated socio-technical system, further sources of expert knowledge should be integrated into the first stage of the process where alternative futures and their constituents are defined. While Rhyne [7] advocated the use of Delphi to extract information early on and Coyle et al. [13] noted the benefits of obtaining inputs from experts, our project is the first to implement this expert elicitation method. Following Coyle and Yong [15], we suggest creating a mind map to structure this expert input to yield the defining elements of the sector-factor array.

3. **Factor exclusivity:** We underline the particular importance and extra attention which needs to be paid to exclusivity in the sector-factor array. This is because of the multiple interdependencies across different sectors shaping complex technical systems, which necessitate simplifications when defining the factors. Delineation between sectors captures the principal underlying socio-technical aspects without crossing over the sectors.

4. **Dynamics:** There are two dimensions in defining the dynamics of many real-world systems that FAR needs to incorporate: logical ordering and timescales. Neither identifying event timescales nor assigning likelihoods to their occurrence are formally part of the FAR method, since it is not explicitly a forecasting tool. The logical ordering of processes or activities is a strong constraint. The engineering practicalities of many technical systems necessitate considering the logical sequence of events giving the potential for critical junctures (or

‘branching points’) to determine future states of the system. The temporal spread of these ordered events is a less strong (but ever-present) constraint since technology development may occur at different rates, but reach the same end-point. Their co-evolution determines the spread and rate of development. Project team knowledge and expert feedback (stage 4) identify the correct logical ordering, and an expert workshop identifies the temporal spread.

5. **Uncertainty:** To accounts for degrees of uncertainty we suggest using a symmetric negative and positive range to indicate inconsistency/consistency. Previous studies have used only a single negative value for conducting the pairwise comparison of factor consistencies [15].

We summarise the differences between the original and our augmented FAR method in Table 2.

Table 2. Comparison of core and augmented FAR method

		Step 1. Visualise the future	**Step 2. A symbolic language of the future**	**Step 3. Relax the anomalies**	**Step 4. Compose scenario outlines**
Core method	Purpose	Identify a set of images of future prospects	Distil sector/ factor array from future images	Eliminate inconsistent configurations	Develop scenarios
	Input	Project team	Project team	Project team	Project team
	Disciplinary expertise	No specific reference to multidisciplinary expertise			
Augmented FAR	Purpose	Identify a set of images of future prospects	Identify the constituents of sector/ factor array and ensure factor exclusivity	Eliminate inconsistent configurations and address uncertainty	Develop scenarios with explicit consideration of dynamics
	Input	Project Advisory Group (N=9)	Literature review, Expert interviews (N=18), Online survey (N=77 & 44)	EIDOS software/ project team	Expert workshop (N=23), Project Advisory Group, project team
	Disciplinary expertise	Multidisciplinary project team			

4. Implementing the augmented FAR

This extended method was developed in a 24 month project, and implemented through face-to-face team meetings, interviews, a two-stage Delphi, and four workshops specifically focusing on developing the scenarios. A project advisory group (PAG, N=9) was drawn from experts across the industry (N=5), policy (N=2), NGO (N=1) and academia (N=1). The PAG met at six-monthly intervals over half-a-day meetings on voluntary basis. Following project team discussions (used in the standard method) and review of peer-reviewed and grey literature, we followed a participatory process by conducting interviews with individual experts (N =18) representing power generation, transmission, and distribution, consumer rights, policy and market regulation, and ICT infrastructure to identify drivers and barriers to the development of SGs [62]. The interviews took place during a three-month period, typically taking 60-90 minutes (all under 120 minutes). Building on the interview data, a further two rounds of data collection from a wider range of experts were conducted using anonymised online surveys. The two-stage survey (N =77, N=44) applied the Policy Delphi method [77]; stage two participants had to have completed the stage 1 survey. These surveys occurred over a six month period. This identified the drivers and barriers associated with SG growth and the essential functions likely to be required to provide for development of SGs in the UK context. This process also allowed us to identify interdependencies in the process of SG development [48]. The dynamics of scenarios were discussed and developed in an expert workshop (N=23) including representatives of DNOs, Ofgem, the transmission system operator, policymakers, ICT companies and energy consultants. The employment sectors of the participants in each activity are given in Table A.1.

Previously documented FAR projects have the 'study team members' [9] or 'the analysts' [7] undertake steps 1 and 2. This exercise expanded the project team's expertise through inputs from the experts via PAG meetings, interviews and the online Delphi survey. Potential overlaps of the experts who have contributed to interviews and the online survey means the project gathered insights from 77 to 133 experts. These extensive data collection exercises provided strong foundations for our implementation of the augmented FAR. The insights emerging from these participatory methods were analysed and refined by the multidisciplinary team with expertise spanning across energy systems modeling, power system engineering, energy policy and environmental psychology. In four workshops, the project team identified the following seven sectors: Market (M), Users (U), Data and information (D), Supply (S), Policy (P), Investment conditions (I), and Networks (N). These sectors are abbreviated as MUDSPIN to ensure that no sector takes priority or importance over the others [7,13]. The main characteristics of these sectors are as follows:

1. *Market* describes the structure of the energy industry, specifically the growth of new energy-related services (for example, new aggregators, new and extended approaches to energy services, community trading and others) and whether the providers are the incumbents or new market entrants.
2. *Users* include electricity consumers (residential, commercial, and industrial), the extent to which they are willing and/or able to respond to signals to adjust their energy usage (active) or not (passive), and the total national level of demand.
3. *Data and information* captures the source, scale and granularity of data available to the transmission and distribution network operators.
4. *Supply* represents power generation characteristics, which can be achieved by various technologies.
5. *Policy* focuses on the availability of incentives to drive SG development and whether or not there is effective co-ordination.
6. *Investment conditions* reflect the relative expense of capital and whether the regulatory framework is conducive to investment for innovation.
7. *Networks* take into account the extent of active management within networks and reflects the smartness of the wider system to accommodate more complex loads, for example, greater levels of renewables, distributed generation, heat pumps, and electric vehicles.

Each sector has mutually exclusive ‘factors’ representing different potential future states of the sector (Table 3). The mind map was useful for distilling out the factors and developing a common language across the team. Keeping the factors descriptive avoids the need to specify detailed rates of technological development, however, some aspects merited specific inclusion. For example we treated *users* as a corollary of consumer engagement as this was the only sector that could include the social aspects of SG directly. This sector combines an effect (level of demand) and the social circumstances that may influence the flexibility of that demand (whether the users are active or passive). To the best of our knowledge no previously documented FAR projects have brought different elements together in the same factors in this manner. Using this approach enabled us to finesse the differences of definition which inevitably arise, but perhaps have similar practical consequences for the physical system (delivery of power). The term ‘active’ and ‘passive’ has different meanings within the electricity sector. For power engineers, an active consumer could be one who adopts (or allows the installation of) a device for demand-side management which then remains ‘invisible’ to the consumer – a so-called ‘fit and forget’ solution. For others, an active consumer could be one who makes frequent decisions about their power use.

The 2008 Climate Change Act [78] set an ambition of achieving significant emissions reduction target by 2050, which has focused the time horizon of many UK energy scenarios to 2050 [31,53,54,56–58]. Our study also adopts time horizon of 2050. One effect of this was to rule out substantive deployment of nuclear fusion.

Table 3. The seven sectors and their factors (the ‘sector-factor array’)

Market	**Users**	**Data & information**	**Supply**	**Policy**	**Investment**	**Networks**
Low growth in new energy related services, existing actors	Low increase in demand, passive consumers	Customer billing info only (the BAU case), plus basic network data	Characterized by inflexible generation	Weak incentives, no coordination of smarter energy delivery by government, regulator or similar	Low-cost capital, constructive regulatory investment framework	Passive distribution network management
Low growth in new energy related services, new (additional) actors	High increase in demand, passive consumers	Aggregated historical data only	Characterized by flexible generation	Strong incentives, no coordination of smarter energy delivery	Expensive capital, constructive regulatory investment framework	Partially active distribution network management
High growth in new energy related services, existing actors	Low increase in demand, active consumers	Aggregated near to real-time data available	Characterized by variable generation	Weak incentives, coordination of smarter energy delivery	Low-cost capital, obstructive regulatory investment framework	Fully active distribution network management
High growth in new energy related services, new (additional) actors	High increase in demand, active consumers	Disaggregated near to real-time data available		Strong incentives, coordination of smarter energy delivery	Expensive capital, obstructive regulatory investment framework	

4.1 Conducting the pairwise consistency checks

Using more than a single negative value for inconsistency accommodates degrees of uncertainty in greater depth in environmental and social systems (Table 4). The scale captures the plausibility of a world in which the two variables occur together, and therefore degrees of 'implausibility' are important because they will result in a more detailed range of scenarios. Using zero to represent neither consistency nor inconsistency, the temptation to apply a middle value is removed.

Table 4. The interpretation for the pairwise comparison matrix

Value	Inconsistency	Consistency
-3	Inconsistent in all circumstances	No consistency
-2	Inconsistent in most circumstances	Unlikely to be consistent
-1	Inconsistent in some circumstances	Unlikely to be consistent
1	Unlikely to be inconsistent	Consistent in some circumstances
2	Unlikely to be inconsistent	Consistent in most circumstances
3	No inconsistency	Consistent in all circumstances
0	Neither consistent nor inconsistent	

The pairwise consistency scoring of factors was conducted by the project team, split into pairs for each of the sectors with cross-checking carried out by a different pair of team members. The decisions for assigning a value to each pairwise comparison were based on all of the evidence assembled in stage 1 of the augmented FAR method. Notes to justify each decision were kept and validated in the cross-checking stage. Differences between the primary and cross-checking steps were resolved (and recorded) by the two pairs of team members. Any remaining differences were resolved by the team collectively. The final array is shown in **Figure 3**. Only two of the 253 pairwise comparisons were considered to be neither consistent nor inconsistent, suggesting that the sectors and factors used are appropriate and unambiguous.

		Users				Data & Information				Supply			Policy				Investment conditions				Networks		
		Low increase in demand, passive consumers	High increase in demand, passive consumers	Low increase in demand, active consumers	High increase in demand, active consumers	Customer billing info only (the BAU case), plus basic network data	Aggregated historical data only	Aggregated near to real-time data available	Disaggregated near to real-time data available	Characterized by inflexible generation	Characterized by flexible generation	Characterized by variable generation	Weak incentives, no coordination of smarter energy delivery	Strong incentives, no coordination of smarter energy delivery	Weak incentives, coordination of smarter energy delivery	Strong incentives, coordination of smarter energy delivery	Low-cost capital, constructive regulatory investment framework	Expensive capital, constructive regulatory investment framework	Low-cost capital, obstructive regulatory investment framework	Expensive capital, obstructive regulatory investment framework	Passive distribution network management	Partially active distribution network management	Fully active distribution network management
Market	Low growth in new energy related services, existing actors	3	1	1	-2	3	2	2	1	1	2	-1	3	2	2	1	2	2	1	2	3	2	1
	Low growth in new energy related services, new (additional) actors	1	1	2	-1	-2	-1	1	2	1	1	1	1	1	2	2	2	2	1	2	1	1	1
	High growth in new energy related services, existing actors	-1	1	1	2	1	2	2	2	0	1	2	1	2	2	2	2	1	-2	-2	-2	2	3
	High growth in new energy related services, new (additional) actors	-2	2	2	3	0	2	2	3	1	1	3	-1	1	2	3	2	1	-2	-2	-2	2	3
Users	Low increase in demand, passive consumers					3	2	2	2	3	3	-3	3	3	2	2	1	1	2	2	3	1	1
	High increase in demand, passive consumers					2	2	2	2	3	3	-3	3	3	2	2	1	1	2	2	2	1	1
	Low increase in demand, active consumers					-2	-1	1	2	1	1	3	2	2	3	3	2	2	-1	-1	-3	2	3
	High increase in demand, active consumers					-2	-1	1	3	1	1	3	2	2	2	3	2	2	-1	-1	-3	2	3
Data & Information	Customer billing info only (the BAU case), plus basic network data									3	3	-3	3	2	-2	-3	-1	-1	2	3	3	-3	-3
	Aggregated historical data only									2	1	-1	3	2	-1	-1	3	2	-2	-3	3	-2	-2

	Aggregated near to real-time data available									1	1	2	-3	-1	2	3	3	2	-2	-3	-3	3	3
	Disaggregated near to real-time data available									-1	1	3	-3	-1	2	3	3	2	-2	-3	-3	3	3
Supply	Characterized by inflexible generation												3	-2	-1	-2	2	-1	2	-1	3	1	-2
	Characterized by flexible generation												3	-1	-1	-1	1	3	1	2	3	1	1
	Characterized by variable generation												-3	1	2	3	3	2	1	1	-3	2	3
Policy	Weak incentives, no coordination of smarter energy delivery																1	-1	3	2	3	-1	-3
	Strong incentives, no coordination of smarter energy delivery																2	-1	2	1	1	1	1
	Weak incentives, coordination of smarter energy delivery																2	1	-1	-2	-1	1	2
	Strong incentives, coordination of smarter energy delivery																3	2	-2	-3	-2	2	3
Investment conditions	Low-cost capital, constructive regulatory investment framework																				1	3	3
	Expensive capital, constructive regulatory investment framework																				2	2	2
	Low-cost capital, obstructive regulatory investment framework																				2	-2	-2
	Expensive capital, obstructive regulatory investment framework																				2	-3	-3

Figure 3. The finalised consistency matrix

We used the Parmenides EIDOS software (version 8.2) to calculate the overall consistency rating of each configuration and rank them accordingly (Section 0). Using the second round of combination elimination removes those configurations which have a highly inconsistent sector/factor (but which are otherwise plausible). This holistic assessment is an important step in ensuring the physical and social consistency. The remaining configurations are clustered together, then combinations containing some intuitive inconsistency were removed. This step blends with the scenario construction stage and exploits a strength of FAR as a reflexive process. Furthermore, this blended step avoids the need to evaluate consistency of pairwise combination with a third sector/factor, reducing computational complexity.

4.2 Composing the scenarios

By using dichotomous (i.e. yes/no) pairwise consistency rating, previous practitioners note significant reductions in the number of plausible configurations to consider in stage 3, ranging from 99% (from 189,000 to fewer than 100) [7] to 97% reduction (from 14,400 to 403) [79]. The use of a graded consistency rating necessitates an alternative approach as the number of plausible configurations can be reasonably large. When using a degree of consistency rating varying from 0 to 3, Coyle and Yong [15] worked with under 100 (91 out of 4608) configurations that include pairwise consistency ratings of 2 and 3. In our work, we followed this latter approach to work with configurations that include pairwise ratings of 2 and 3.

EIDOS calculates the consistency rating of all configurations, which are listed in descending order. The highest consistency ratings are characterised by two configurations ($M_4U_4D_4S_3P_4I_4N_3$ at 2.90 and $M_4U_3D_4S_3P_4I_4N_3$ at 2.81). Of the remaining configurations, a minimum of two and a maximum of 38 yield the same consistency rating which are then subjected to 'gestalt' appreciation and 'diversity' checks. As the software calculates a straight average of the 21 pairwise consistency ratings, occasionally a configuration with otherwise very high internal consistency may contain one inconsistent pair. Following previous approaches [7,15], we took into account the first 100 most consistent configurations with a consistency rating going down to 2.19. Likewise, there were cases where an individual pair was consistent but the configuration viewed as a whole did not appear consistent. A total of six configurations (with consistency ratings between 2.29 and 2.19) were ruled out throughout this part of the process.

It is important to include consistent, but diverse, configurations. Of the first 100 configurations only 14 had flexible generation (S_2) as a factor and many were similar. Hence, we expanded the range of configurations considered by fixing supply to flexible generation (using functionality of EIDOS). This gave a further 53 configurations with a pairwise rating of no less than zero that yield average consistency rating varying from 2.0 to 1.76 for flexible generation.

Two members of the team worked collaboratively to spell out what each consistent combination meant. Previous FAR practitioners [7,9,13,15] highlighted the importance of familiarisation with the configurations – a form of '*personal acquaintanceship*' [15, p.274]. Our experience is that by the end of this process we were able to recall any combination of MUDSPIN by heart. Transition from individual configurations to scenarios is by far the most subjective part of the FAR. The objective is to arrive at a progression of combinations stretching out into the future, always applying the gestalt appreciation of 'can I see *this* world leading to *that* one?' [15, p.275]. In our case this involved grouping and re-grouping clusters of configurations bringing them together in the Faustian Tree. Each of the clusters is accompanied by a few words describing it as an aid to the process.

In total, we worked with 147 configurations. Coyle et al. [13] recommend a four-step approach in stringing configurations together to create plausible timelines: (i) grouping, (ii) merging, (iii) creation of timelines and (iv) scenario generation. They mention the perceived dominance of a factor as a key criterion for identifying and merging the groups. In our case, the clustering followed the principle that no more than three of the seven MUDSPIN configurations can move by one factor up or down [79]. These clusters act as building blocks, describing stages in the progression of each scenario. The timelines and sequences of events were then assessed in an expert workshop (N=23) in detailed discussions with small groups of 7-8 participants.

When developing the timelines and sequences of events, we used the insights from the second phase of the online surveys on the nature and types of interdependencies – the things which must happen in order for the key characteristics to come about [48]. Some practitioners used minimum and maximum time diffusion values for each factor which could result in overlooking their cross-impacts on other factors [13]. The insights generated from the expert survey guided identification of the 'order of things' in a team exercise (subsequently discussed and assessed in an expert workshop). We sought expert opinion on the possible timelines of events that we had already developed as the Faustian Tree. Results from the workshop were fed back into the project and the Faustian Tree was refined further (Figure 4) and it became apparent which of the timelines would be developed into the fully-fledged narrative scenarios. In some cases, the experts disagreed in terms of the absolute time at which an event or SG function might occur, but were in stronger agreement about the relative point at which these might occur in different scenarios.

4.3 UK Smart grid scenarios

We outline each of the four final scenarios; extensive descriptions are available [61]. It is implicit in the following scenarios that the degree and geographical extent of smartness will vary. Unless stated otherwise, smart development occurs where five essential functions (defined by the experts) are achieved: 1) balancing a power grid with high volumes of intermittent renewable resources, 2) increasing observability and controllability of the power grid, 3) allowing integration of active loads, 4) enabling deployment of demand-side reduction technologies and active network management, and 5) integration of energy storage.

We identified some scenario 'building blocks' that instigate transition to a number of alternative steps depending on changes in factors. An example of such a 'branching point' [80] is step G in **Figure 4** where depending on the emerging supply mix and consumers becoming active or remaining passive, end-points F, Q or J might be reached. Whilst consumers remaining passive reinforces the existing pathway, active consumers branch to a new pathway thus setting an example of extreme uncertainty. While the original FAR method does prevent the identification of branching points, these might not naturally arise. The novelty of augmented FAR is that those branching points were identified by the experts in Delphi process, increasing the transparency and objectivity of the method. The next participatory method, the expert workshop identified the effects and consequences of the branching points which are summarised in Table 5.

In the **Minimum Smart** scenario, a lack of coordination and long-term vision coincides with weak consumer acceptance of smart technologies and demand-side measures. This scenario, in effect, has a lack of strong drivers for any meaningful increase in network smartness. Weaker drivers do exist, however, and so there is not a total absence of smartness, although the preponderance of gas generation means there is less of a need for demand-side flexibility.

In contrast, the **Groundswell** scenario sees very strong consumer interest in and engagement with the energy system, resulting in at least partially smart development arising from increased national concern over the declining capacity margin and the upward trend in energy prices. This eventually causes a radical paradigm shift, with rapid growth in community and local authority-run electricity generation and supply and even some local network management.

The **Smart Power Sector** scenario is defined by consumers highly resistant to changes in the way they use and conceptualise energy. The application of smart technologies can therefore only really take place 'behind the scenes', and this means there are limits to what can be achieved. Policy and regulatory guidance are firm, however, and DNOs are incentivised to do what they need to do when, including transition to acting as system operator. Later in the scenario, high numbers of EVs appear and there is significant generation from renewables. There remains some possibility of actions on the demand side of the meter where this does not rely on significant action from the consumer.

Smart 2050 sets the upper boundary for our scenarios. Well-coordinated and coherent policy action builds strong consumer engagement, resulting in a greater number of smart grid-support services. Engagement differs here from the Groundswell scenario in that it is driven by policy. Strong coordination and the availability of cost-effective options lead to the emergence of a different set of technologies and change the nature of the smart grid correspondingly.

Table 5. The branching points and their descriptors.

Branching Point		Minimum Smart	Smart Power Sector	Smart 2050	Ground-swell
Label	Descriptor				
B	RIIO leads to little change	✓	✓		
C	RIIO stimulates change		✓	✓	✓
E*	Flexible generation. Constructive regulation. Strong incentives.		✓	✓	✓
G	NES emerging. Flexible generation. Strong policy co-ordination. Constructive regulation. Some near-to-real-time data.		✓	✓	✓
I	Policy driven change. Little enagagement. Lower cost of capital. Move to inflexible generation.		✓		✓
L	Existing actors provide NES. Active consumers. Economic recovery and cheaper capital. Policy weakening.		✓	✓	✓
N*	Consumers very active. Existing actors dominant.				✓

* Note that points E and N leads to three different end-points in the same scenario.

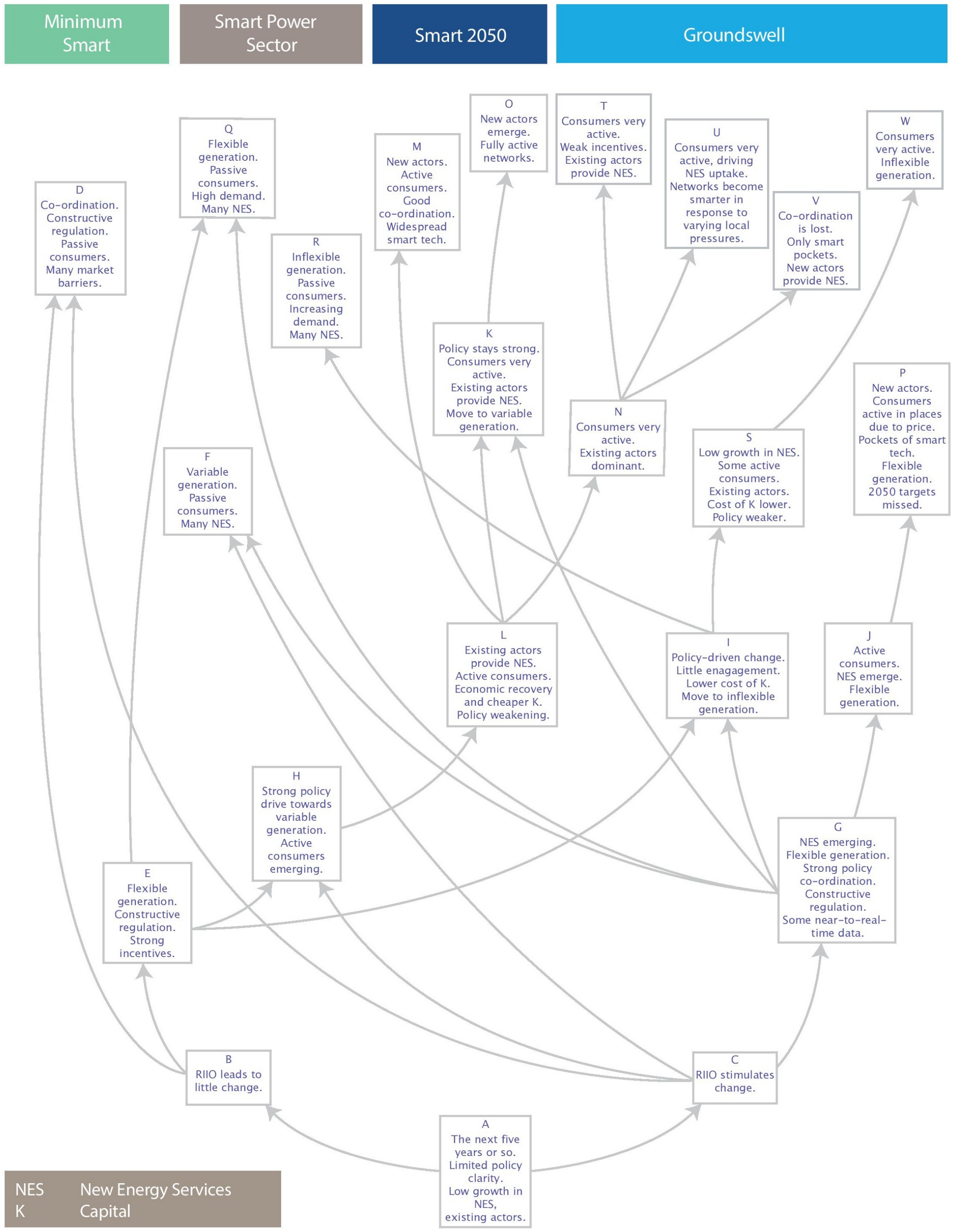

Figure 4: The Faustian Tree

Source: Balta-Ozkan et al. [61]

5. Discussion

While there is broad agreement on how smart grids can enable the most cost-effective operation of a low carbon grid, there are many uncertainties [62]. Some of the unknowns are: the degree of smartness required (or that which can be achieved), when it will be required, how quickly it can and will develop, the new actors that may be required, the order in which increasing smartness will occur and the level of spatial variation across a network as well as the design of pricing mechanisms and emergence of new business paradigms [35]. This evolving uncertainty needs to be considered when developing policy and regulation and will need to inform the instruments chosen to incentivise different stakeholders, including potential new stakeholders. The multi-stage process described here allowed for the perspectives of the widest possible set of stakeholders to inform our scenarios and to thus ensure that they reflect a diversity of opinion, accounting for diverse forward planning needs.

The outcomes are defined by complexity, reflecting both the wide range of often interdependent factors and the divergence of stakeholder views on the definition, direction and potential added value of SGs [81]. Therefore flexibility is a key premise of SG [82] meaning that technical, economic and social elements of the system should be designed to be inherently flexible, allowing for current unknowns to emerge, such as new energy services and associated companies.

Public engagement emerged as a key determinant of the likely extent of SG, but this should be of a political nature and not purely of economic interest [83]. Scenarios can help to inform this engagement process by improving openness and presenting multiple perspectives to the public [28]. Stakeholders, including policymakers but also other consumer facing actors, can plan around these degrees of engagement to inform their own future needs regarding investment and regulatory evolution. By discovering the inherent interdependencies (using expert inputs) in different options and branching points across multiple pathways, our findings reveal credible alternative energy futures in the form of stories and narratives [84,85] that can be used to engage the different stakeholders and assess the implications of alternative decisions. Our Groundswell Scenario offers a much more decentralised energy future signified by flourishing community and local energy generation, supply and network management. However, a lack of consumer engagement pushes the industry to build extensive instrumentation and control behind the meters to manage the grid in Smart Power scenario. Each scenario reflects complex interaction of the key factors identified by our stakeholders, and the variety of ways these might interact to produce diverse outcomes. They represent different directions for the sector, reflecting both potential for action and inaction by different stakeholder groups. Our consideration of this complexity, and the scenarios which emerge from it, should prove valuable for policymakers, including both government and regulators as well as the wider public. Only through such a dialogue, in line with the principles of anticipatory governance [86,87] can the opportunities and challenges SGs present can be monitored and managed. More specifically, the augmented FAR enabled us to identify and manage the interaction of these multiple aspects of SG development in a systematic and transparent way.

While some scholars have previously incorporated Delphi and semi-structured interviews into scenarios [88], our study is their first application to FAR to give a '*structure*' [15] to the key stage of FAR in identifying sectors and factors. The original FAR starts with the imagining of alternative futures within the project team to create a common set of future field prospects, we incorporated input from a wider set of experts through the use of a PAG, expert interviews, the two-stage policy Delphi and an expert workshop. Collectively, this multiple stage process is an important step towards ensuring scenario objectivity [89].

Pereverza et al. [90] suggest transparency, reliability, coverage, completeness, relevance/density, creativity, interpretability, consistency, differentiation and plausibility as key criteria for scenario selection. In our case, we found a tension between selecting the most consistent configurations (consistency) and those describing a novel narrative (differentiation). Their analysis is limited to a five-dimensional and three-dimensional problem space (respectively yielding total combinations of 72 and 12 to work with), where scenarios are defined as end points. The participatory process we followed yielded a seven-dimensional problem space with many scenario configurations embodying varying degrees of consistency. As SG development is a process where the interaction of different network technologies, data access and management rules, end user behaviours, availability of capital etc. influence the availability of future possible options across all dimensions of scenario space, the logical ordering of scenario configurations, their timescales and interactions do not necessarily follow a linear path. This 'extreme complexity' necessitated stringing groups of similar scenario configurations together (scenario 'building blocs') and critically assessing changes in several factors that might change a scenario pathway.

When ranked by descending consistency many configurations that are similar both in character and in overall consistency value end up grouped together. For example, the most consistent configurations were those that described either 1) the state of the energy system as it is currently (or has been in the recent past) or 2) how it might look after a transition. Regarding the first case, we concur with Coyle et al. [13] on the importance of not relaxing the base case. Conceptually, the second case is not surprising either because the real value of a SG emanates from its capability for enabling the cost-effective management of a grid with large shares of renewable resources and controllable loads. In the UK context, the economic value of demand side response, a key capability of SG, is projected to be £8.1 billion per year by 2030, along with storage and interconnection [91]. Extensive discussions within the project team, working in pairs and with conclusions cross-checked by another pair, enabled the development of such a shared understanding. This extensive team-discussions also prevented us from facing difficulties in deciding on particular relaxations which might arise due to ambiguities in sector/factor definitions [13].

The corollary to having many configurations characterising either very low carbon, highly smart or base cases is that the states in between appear somewhat under-represented. Although this was a source of concern initially, we concluded that this is fair: it is self-evident that transition describes the dynamic period of upheaval and uncertainty between two more static states, and the lower consistencies of the 'transition period' configurations reflect this. Such periods of instability/ inconsistency are supported by a number of theoretical frameworks which explain energy transitions as interactions between niche (micro), regime (meso) and landscape (macro) levels [92] or due to coevolution of technologies, institutions, ecosystems, business strategies and user practices [93].

The low ratings for the states between the extreme configurations could have resulted from our attempts to experiment with the method in order to accommodate a greater number of variables in the sector-factor array. Whilst we followed the principles outlined by Duczynski [79] in developing the clusters, in practice our implementation was more flexible as some of our factors included movement in two aspects. However, this flexibility is in line with recommendations from Coyle [43, p.7] which states that '*the arrangement in the columns does not mean that a Factor can only change to the next adjacent state*'.

Despite equal treatment of any possible future state in a systematic way, we were surprised to find many configurations yielding similar average consistency ratings. This might be one of the side effects of us employing negative as well as positive values in assessing pairwise consistency of the factors. One potential solution to analyse 'out of the bound' scenarios could be the use of 'slot machine technique' by allowing the sectors to take unspecified or free values [11]. However, the random nature of such process might void the structured and 'tractable' nature of FAR.

Our observations from the augmentation and implementation of FAR method are as follows:

- These modifications to the FAR methodology allowed for the system under examination to have transitions from one stable state to another, but to pass through periods of instability/inconsistency. We suggest that this reflects the practical transitions which occur in real-world systems with long turnover times for infrastructure.
- We observed that for our socio-technical system – and we expect this will be general – it is possible that even very 'non-constrained' methods of scenario development, such as FAR, may be subject to various normative constraints.
- We observed that for a regulated socio-technical system with both long-lived infrastructure and fast-moving technical developments, using a varying degree of inconsistency in a pairwise matrix gave greater degrees of freedom in the plausible pathways. We consider that this had an impact on how the branching points developed.

There is no doubt that the development of SGs is a social problem as they offer a means of enabling the technologies widely seen as essential to addressing the energy trilemma [94]. Our augmented approach has utilised the insights and knowledge of a substantive body of expertise across industry, policy and academia. Even though the online surveys were mostly dominated by industry and engineering experts, no significant bias by expertise group was detected [48]. Yet, this data collection could have been guided by a more explicit consideration of different types of stakeholders such as the aggregators, new energy suppliers and technology developers to improve the rigour of the study [95]. We recognise that our stakeholder groups can only represent the current landscape.

6. Conclusions

For the first time, we have applied FAR to scenarios for a complex socio-technical system. One of the defining characteristics of SG (and the power generation and distribution system in general) is that it is a safety critical system which operates in a regulated market. The use of branching points is particularly well suited to socio-technical systems where policy decisions can alter the pathway or scenario outcome. This provides a sense of the order and timing of decisions (dynamics) required to move to a particular pathway, or to avoid an undesirable outcome. While the methodology was applied to develop scenarios specific to SG growth in the UK, it should be applicable in other territories. We would expect to see different scenarios emerge since differences in national frameworks include core elements we considered, such as policy and regulatory goals and architectures, existing institutional paradigms, focus on different social and economic outcomes, public attitudes, current technology, environmental commitments, renewable energy resource potential and others.

The augmented FAR methodology accommodated sustained input from experts over a prolonged period and using methods convenient to them. However, there are limitations to developing projections with diverse sets of expert stakeholder groups operating mixes of well-understood and novel technologies with disparate sector practices and regulations. In particular we highlight the time-consuming nature of generating robust scenario sets. In a large study, experts are only willing to give input in well-defined ways in day-long sessions (at most). Therefore, the original FAR method of cycling is inappropriate where there is a significant break between steps. It is also in the nature of the modern employment market that retaining the exact same group of experts is unlikely. We suggest that using feedback and validation cycles at each stage offers advantages over the core method for complex studies of national-scale socio-technical systems, especially those of critical national need. We recommend using the augmented FAR for issues of extreme complexity, particularly multi- or trans-disciplinary socio-technical problems for real-world systems. Such systems may be characterised by multiple stakeholders of widely differing scales encompassing individuals, multi-national corporations or national and supra-national government entities, extensive policy or regulatory requirements, and decisions with multi-decadal or intergenerational effects. The problems may be characterised as having demands on some dimensions which can change at rates far faster than the long-term effects, perhaps some having the possibility of major changes occurring faster than a year. In addition, suitable systems may exhibit constraints such as the predetermined logical ordering of some events and varying minimum temporal periods between them.

It is largely inevitable that electricity supply industries in the developed world will become smarter as a result of the changing requirements that society is placing on electricity systems as part of the decarbonisation process. The evolving nature of its regulatory framework reflects the uncertainties associated with the development of SG in the UK. This has been at least partially acknowledged with the adoption of the RIIO framework (Revenue=Incentives+Innovation+Outputs) as the central mechanism for transmission and distribution network regulation in the UK, with its intention of incentivising network operators to innovate their planning and risk management for the new circumstances as they develop [39,96]. While initially RIIO was designed to cover an eight-year investment period, the fast pace of technological development and inherent uncertainties associated with the changes in energy markets saw a reduction in the price review period to five years [97]. There is of course no guarantee at this stage that RIIO will be effective in meeting longer term goals. We note that that experts considered there was potential for both the Smart Power and Minimum Smart scenarios even if RIIO failed.

As scenarios extend further from the present the difficulty of extrapolation increases as the uncertainties cascade. As with all scenario generation methods, the outputs of the augmented FAR are not intended to be accurate predictions of the future. Their usefulness derives from the process: identifying the widest possible set of issues, potential barriers, and in particular the interdependencies between different technological realms, the requirement for policy and regulation to account for these, and varying approaches and practices of the sector experts. Bringing these together allow for policymakers and other stakeholders to be better informed of opportunities and points for action to enable change while reducing scope for unexpected consequences. We expect that our scenarios can better inform anticipatory governance and subsequent planning which can be made more appropriate to the different routes that SG development might follow.

The development of scenarios which can increase understanding of the ways in which policy concerning different elements of increasing systemic smartness might interact allows insights into possible problems ahead of their emergence and for more informed policy and regulatory planning. The need for consideration and coordination of different elements of planning, policy and regulation are essential and augmented FAR enables unpacking these multiple interdependencies.

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Appendix A

Table A.1 Summary of the sectors which participants represented.

Sector	**Interview (N=18)**	**Round 1 (N=77)**	**Round 2 (N=44)**	**Workshop (N=23)**
Academic	6%	33%	25%	9%
Consultant	11%	9%	0%	17%
Consumer / community interest group	11%	13%	5%	13%
Generator	11%	2%	2%	9%
Network Operator	33%	19%	25%	13%
Policy	11%	5%	2%	13%
Regulator	6%	2%	2%	4%
Supplier	6%	8%	9%	9%
Other	5%	11%	30%	13%
	(100%)	100%	100%	100%