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Are we seeing clearly? The need for aligned vision and supporting strategies to deliver net-zero electricity systems.

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1. Introduction

This paper explores trends, step changes and innovations that could impact the integration of renewable energy into electricity systems. It aims to enhance our understanding of system-wide issues, and provide insights into some of the mechanisms by which these issues may be overcome.

Countries around the world are embarking on transitions to deliver net-zero energy systems that restrict greenhouse gas emissions in line with the Paris Agreement (UNFCCC, 2018). This requires significant investment in renewable energy projects, including wind and solar, which are thought to be major contributors to decarbonising energy supply (IPCC, 2018). It also requires transformation of other energy services, such as mobility and heating and cooling, which may increase demand for low-carbon electricity (IEA, 2019).

While wind and solar offer significant opportunities to deliver societal, environmental and financial benefits, there are technical, institutional, and social challenges associated with their integration into existing infrastructure (Klessmann, Nabe and Burges, 2008; IRENA and IEA-ETSAP, 2015; Martinot, 2016, Eyre *et al.*, 2018). Renewable resources are typically non-dispatchable, variable, and in some cases align poorly with peak grid demand (Steinke, Wolfrum and Hoffmann, 2013). The key challenge for a rapid renewables transition is to integrate these variable resources into existing power systems (Martinot, 2016; IRENA, 2019) while maintaining a reliable, secure and affordable electricity system.

Reliability is a measure of how well the whole electricity system meets demand. Some studies show that it is possible to integrate high levels of renewable electricity via a combination of wind and solar with flexible and dispatchable renewable technologies (e.g. hydro-electricity with dams, geothermal, biomass) and demand side response measures (Lund and Mathiesen, 2009; Heide *et al.*, 2011; Rasmussen, Andresen and Greiner, 2012; Schlachtberger *et al.*, 2016; Diesendorf and Elliston, 2018). Other studies question the degree to which reliability can be maintained when factors such as temporal and spatial variability are also considered (Heard *et al.*, 2017).

A reliable electricity system is able maintain supply of power to end users in the face of disturbance, which requires operating the system with the bounds of key technical parameters such as frequency and voltage of alternating current, fault current levels, and equipment design limits. If unmanaged, high levels of distributed renewable generation can reduce system inertia, increase frequency volatility, and cause issues with voltage and faults (Dreidy, Mokhlis and Mekhilef, 2017; Telukunta *et al.*, 2017). A variety of measures can help overcome this, including the use of 'synthetic' inertia, contracted demand side response, batteries, synchronous condensers, dispatchable renewable generation, new major transmissions lines, and smart energy systems that integrate across energy vectors at local scales (Mathiesen *et al.*, 2015; Howell *et al.*, 2017; Diesendorf and Elliston, 2018).

In addition to these technical challenges, integrating high levels of renewable energy raises further operational and regulatory challenges (Judson *et al.*, 2020). Renewables, particularly wind and solar power, differ from conventional generation in that they have low- or even negative marginal costs and their output is variable (Morales *et al.*, 2014). Variable output renewables increase the value of flexibility in electricity systems. This value is often not reflected in wholesale markets, creating a missing money issue where markets do not reflect customer demand and associated investment signal for reliability (Hogan, 2017). IRENA have explored approaches to adapting market design to overcome this, including: improving temporal and locational signals in short-term markets; adapting balancing markets to better reward flexibility; and enabling appropriate capacity or adequacy mechanisms to allow mature renewable participation and minimise distortions with other electricity markets (IRENA, 2017).

Alongside market reform, given that distributed energy resources are connected to local electricity distribution networks, many actions required to integrate renewables occur locally. Integration requires consideration of network access, planning and smart (or active) grid operation by network operators (IRENA, 2017). This includes valuing flexibility services from distributed energy resources and demand side response. Aligned technologies that can support the technical integration of renewable energy, such as electricity storage, can present further regulatory challenges, e.g. related to ownership, planning issues, co-location with existing renewables and, network access and charging (Morris and Hardy, 2019).

As reliance on existing market structures becomes increasingly problematic, it is necessary to consider alternative business models and new ways of creating value within decarbonised systems, enabling distributed energy assets to participate in the system (Eyre *et al.*, 2018; Morris *et al.*, 2020). Supported by the digitalisation of energy systems, there has been an emergence of digital energy platforms, providing a space for users to interact and access new products, services and resources, creating new value streams for distributed assets (Kloppenburg and Boekelo, 2019; Morris *et al.*, 2020). A challenge is the timing of regulation of digital energy platforms; regulating too early can stifle innovation and too late could result in locking in consumers to harmful business models (Morris *et al.*, 2020).

In addition to the market and regulatory challenges associated with emerging physical and digital technologies, there are concerns about the ability of existing governance structures to enable the rapid change in markets, investment, innovation and engagement that is now needed to limit global warming (Kuzemko *et al.*, 2016; Seto *et al.*, 2016; Henrysson and Hendrickson, 2020; Höhne *et al.*, 2020; Raybould *et al.*, 2020). The increasingly decentralised nature of renewables means that a low carbon electricity system transition will need to consider issues such as public acceptability (Devine-Wright, 2011; Perlaviciute *et al.*, 2018), community engagement and citizen participation (Bergman and Eyre, 2011; Batel and Devine-Wright, 2015; Ambrose, 2020), and skills, capacity and agency to deliver change (Parag and Janda, 2014; Kuzemko and Britton, 2020). While the pathway for change will differ between countries and contexts (for example, solutions for vertically integrated monopoly utilities will be different from competitive retail markets, and different again from developing nations) there may be institutional challenges due to powerful incumbents resisting change, stifling innovation, or pushing change in a direction misaligned with that required (Lauber and Sarasini, 2011; Fattouh, Poudineh and West, 2019; Gielen *et al.*, 2019; Sareen, 2020).

It is clear that the integration of renewable energy required to drive a net-zero energy transition faces a variety of interrelated technical and non-technical challenges. As can be seen from the literature, these are typically considered independently by experts in their respective disciplines. However, given the complexity of energy system transition and the interdependencies between technical and non-technical solutions, there is a need to bring together a diverse range of understandings and perspectives to explore how these interact across disciplinary boundaries and policy silos (Geels, 2012; Wiseman, 2018; Hall *et al.*, 2020). No previous work has brought a diverse range of sector experts together across the electricity sector to reach some levels of consensus about the variety of trends, step changes, challenges, innovations and interventions that may exist in supporting the integration of renewable energy, and identify key areas requiring policy intervention. This paper addresses this gap and aims to facilitate cross-sector discussions to identify policy implications for delivering a net-zero electricity system.

2. Methods

The current study used a Delphi approach to collect, synthesis, and seek consensus across expert viewpoints on the key challenges around integrating renewable energy into electricity systems and the interventions required to overcome these. The Delphi method was selected given its long-standing use in supporting decision making and identifying areas for policy intervention in complex systems (Helmer-Hirschberg, 1967; Weaver, 1971; Hasson, Keeney and McKenna, 2000). It was also selected to enable the capture up to date insights about renewable energy integration in electricity systems in a timelier manner than could be gleamed from a systematic review of the literature (Franklin and Hart, 2007).

Despite their established reputation as an appropriate method to explore complex issues, Delphi studies are not without challenges, particularly related to reliability and validity (Hill and Fowles, 1975), and while the Delphi approach does outperform statistical groups and standard interacting groups in its ability to accurately predict future events, there is no consistent evidence that the Delphi technique outperforms other structured group procedures (Rowe and Wright, 1999). However, there are a number of factors that can enhance the performance of the Delphi study, particularly the format of the first round and the selection of respondents.

The traditional Delphi method (Gordon and Helmer-Hirschberg, 1964) includes an unstructured first round, in which respondents were asked for their own predictions of future events. From the responses an edited list is prepared and presented to the panel in the second round, seeking consensus on occurrence. However, an alternative approach has emerged in which the first round is structured, and panellists are provided with a preselected set of statements. This structured approach deprives the expert panel from much of its intended role and can prevent participants from indicating the issues they believe to be of greatest importance; given that the value of the Delphi is to generate ideas more recent that the literature and experiences of the researchers it is important that the first round includes a qualitative unstructured component (Hill and Fowles, 1975; Franklin and Hart, 2007).

Regarding the choice of participants, it is important to use informed experts who have high levels of background knowledge, an understanding of relevance, and who bring a diversity of perspectives and expertise (Helmer-Hirschberg and Rescher, 1960; Rowe and Wright, 1999). To enhance their contribution the Delphi process should include a sound recruitment protocol to ensure the “experts” are appropriately defined related to the topic, and that their interest in the topic may minimise drop out (Franklin and Hart, 2007).

In the current study we sought participants who had expertise across a variety of aspects of renewable energy and electricity systems (including supply, transmission and distribution, demand, system balancing, markets, and regulation) aligned technologies (e.g. storage), and across a range of geographic regions. This aimed to ensure an appropriate diversity of expertise and avoid too narrow a representation of viewpoints leading to bias in the study. Participants were purposively invited from academia and other research organisations, industry, government, NGOs, and business. The recruitment process leveraged the larger research programme of which this study was a part, utilising the broader research team and advisory board, who knew or had contacts across a wide range of experts both within the UK and internationally. These experts were contacted and asked if they would be interested to participate (with time and engagement requirements clearly articulated), and were also asked to nominate others they thought might be interested to engage with the study. We aimed for a good level of experience, representation across sectors, and areas of expertise.

The study took place in the first quarter of 2017. Three consecutive surveys were deployed to collect the data. The first round of the Delphi study was based on the original unstructured approach, in which participants were asked to describe up to three influential trends, three step changes and three innovations that they believed could lead to major shifts in the design, operation, or management of electricity systems, including the ability to integrate renewable energy. Trends were defined as “things that are already changing, and which might influence the electricity sector”, step changes as “possible rapid or sudden shifts, shocks, or changes in context” and innovations as “novel policy, economic, social, technical, or legal developments”. For each trend and step change they identified, participants were asked to also outline the challenges (including political, economic, social, technical, legal or environmental) they thought this may present. For each innovation they identified, participants were asked to note the barriers they believed that could hamper their development and deployment, and the factors that might better enable innovation to occur. Participants were also asked to outline what they thought electricity systems could look like in 2050 if substantial efforts were put in across all levels of society.

The qualitative data returned in Round 1 was thematically analysed to identify a set of distinct trends, step changes, and innovations. These were presented in Round 2, where participants were asked how likely each trend, innovation and step change were to occur or continue within 5 years (on a scale of not likely, somewhat likely or very likely), and what impact they might have on the energy system (on scale of low, moderate, or high). Participants were also given space to provide comments on the trends, step changes and innovations, as well as the process and questions of the survey.

To help prevent attrition and reduce survey length, only the top 10-12 trends, step changes and innovations participants thought either most likely to occur / continue or most likely to have significant impact (even if not likely to continue) were taken forward to Round 3. Here participants were shown this shortlist of trends, step changes and innovations and asked to identify which three they believed were most in need of interventions (e.g. changes to policy and/or market settings) to support the integration of renewable energy into electricity systems.

Sixty-one experts participated in Round 1, 39 participated in Round 2, and 32 participated in Round 3. The participation drop-off was not surprising for a 3-round Delphi with a high cognitive load, and we were please to retain over half of the participants between Rounds 1 and 3 (see Table 1 and Table 2 for an overview of the participants' involvement with the sector and geographic area of expertise).

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Table 1: Participants' involvement with the energy sector

Main involvement area	Round 1	Round 2	Round 3
Academia and other research	15	15	8
Community Energy	2	0	0
Consultancy	10	5	5
Government	6	4	6
Industry (Gen, Tx, Dx, Retail)	11	5	6
NGO	1	1	2
Regulation	3	0	2
Other	4[i]	3[ii]	2[iii]
TOTAL	*61*	*39*	*32*

[i] Include involvement from an aggregator, start up, financier, and the Energy System Catapult (ESC)
[ii] Include involvement from an entrepreneur, ESC, and an innovation organisation
[iii] Include involvement from an entrepreneur, ESC, and an innovation organisation

Table 2: Participants' geographic area of expertise (note: many participants noted multiple representation)

Geographic expertise	**Round 1**	**Round 2**	**Round 3**
US total	23	19	11
US (general)	*18*	*14*	*7*
Texas	*1*	*1*	*1*
California	*1*	*0*	*1*
Massachusetts	*1*	*0*	*0*
New York	*1*	*1*	*0*
Northwest states	*1*	*1*	*0*
Rockies	*0*	*1*	*1*
Western	*0*	*1*	*1*
Europe total	20	16	11
Europe (general)	*12*	*6*	*4*
Central Europe	*1*	*0*	*0*
Eastern Europe	*0*	*0*	*1*
Mediterranean	*1*	*0*	*0*
South East Europe	*2*	*0*	*1*
Germany	*1*	*3*	*1*
Netherlands	*0*	*2*	*0*
Slovenia	*1*	*0*	*0*
Nordic regions	*1*	*4*	*3*
Norway	*1*	*1*	*1*
GB/UK	13	10	9
New Zealand	11	5	4
Australia	3	1	0
Africa total	4	2	3
Africa (general)	*1*	*1*	*1*
East Africa	*1*	*0*	*1*
Central Africa	*0*	*0*	*1*
South Africa	*2*	*1*	*0*
India	2	3	0
China	1	2	0
Thailand	1	1	0
Brazil	1	0	0
Middle East	1	0	0
Mexico	1	1	0
Colombia	1	1	0
Russia	0	1	0
Global	3	0	0

3. Findings

The results draw from all three rounds of the Delphi surveys. In this paper we focus on data which present an interrelated chain of insights into the experts' views on challenges and opportunism for integrating renewable energy, and priority areas for intervening. Section 3.1 explores participants' perspectives on what future electricity systems might look like. Section 3.2 identifies how this might be delivered and identifies the ongoing and emerging trends, step changes and innovations that are most likely to occur and to drive energy system impact. Section 3.3 goes on to identify priority areas for intervention and explores the types of intervention necessary to deliver energy system transition.

3.1. Future Electricity Systems

Many participants believed that future systems would have a greater proportion of renewables. Some thought these would be coupled with more reliable low carbon generation (e.g. nuclear, biomass, or carbon capture plants) as well as storage and peaking plants. Others thought it would be possible to reach a zero or near-zero carbon system through a combination of low-cost renewables, storage, and a very active demand side.

In terms of scale, participants talked about centralised power plants providing a base load (and being driven by government), as well as more distributed solutions delivering dispersed and localised generation and benefits. Some participants mentioned the potential for more autonomous local areas, or a system that could operate in macro zones, for example, under emergency conditions, with further islandable areas within each zone. There was also a focus on customer resourced local energy – potentially linked with district heating – with bulk power resources acting as balancing mechanisms.

To manage variability, participants outlined a variety of methods, including the use of hydro resources to meet peak demand, greater levels of storage, and more interconnection across transmission systems. Application of artificial intelligence and automation through uniform, standardised, and well-developed information and communications infrastructure and cybersecurity protocols was anticipated to help support system operation and balance supply and demand.

Demand side management was mentioned by a number of participants, who believed that almost all customers would be engaging in demand management in some capacity, potentially without being aware of their participation. This would be enabled, they believed, through appropriately designed markets and technical infrastructures (e.g. smart meters and batteries) to deliver demand side management without the loss of comfort or convenience.

Markets were another area anticipated change significantly between now and 2050, becoming more dynamic - centred around smart networks, technologies and metering - and more sophisticated through interconnecting local, national and international markets, and including peer-to-peer trading and both inter and intra-community markets. This would engage a wider range of market actors, with implications on governance and regulation. Some participants thought that governance would shift from monopolistic structures to smaller self-governing areas with more flexible jurisdictional authority, while others thought the shift would be toward greater national and supra-national governance structures.

Electrification of heat and transport was an area of disagreement; some believed that there would be large-scale or full electrification of heat and transport, while others anticipated an expansion of district heating schemes. But where electrification does occur, participants mentioned the potential to incorporate energy efficiency and flexibility into the technology, to ensure demand is manageable by the system.

Finally, participants thought customers would become increasingly self-sufficient, with upper class and single-family residences likely to have their own dedicated power supply and/or be a part of a microgrid. Those with lower incomes were anticipated to be part of a cooperative of some kind, connected into a highly automated power system.

3.2. Delivering Energy System Transition

The remainder of the Delphi questions focussed on identifying pathways through which transition could be realised, including drivers and barriers to change as well as opportunities and implications arising from it. During the first round of the Delphi study, participants identified 26 trends, 20 step changes, and 26 innovations (see Table 3).

Figure 1-Figure 3 depict the findings for the top (i.e. highest scores in terms of likelihood of occurrence and/or impact) trends, step changes, and innovations. Findings show that participants believe increasing levels of intermittent, weather dependent generation will be one of the main trends to continue and have one of the biggest impacts on global energy systems. Participants also believed that electrification of loads (including growth in the EV market) could have a relatively high impact, though not as likely to continue as other trends including improvements in battery capacity and performance and declines in cost; the growth in IT capacity and big data; urbanisation; and technological changes continuing to occur faster than policy and regulation.

In terms of step changes, those of most interest (i.e. more than somewhat likely to occur and delivering more than a moderate impact on the energy system) include: renewable energy costs falling to the point that they drive down utilisation of fossil plants; renewables forcing markets to completely re-evaluate wholesale bidding behaviour and regulation; distribution networks operators taking an increased role in managing system balancing; and realised customer opportunities through smart metering and associated tariffs. However, some participants noted that their responses were guided by the timescale provided in the question, with most of the step changes presented being "*likely in varying extents*" with the potential to "*happen – but not inside the 5-year limit*". One respondent argued that "*current inertia inherent in policy making, industry governance, and market and regulatory frameworks, will probably dampen the degree of 'step' change within 5 years. Nevertheless, in terms of the cumulative effect of all the [step changes identified], the potential impact on the energy system even over (say) 10 years would still qualify as a 'step' change*."

Table 3: Trends, step changes, and innovations identified by Delphi participants

Trends	
Increasing levels of intermittent, weather dependent generation capacity	Deregulation of prices in electricity markets
Increased quantities of natural gas fired generation capacity	Increasingly urban populations
Trend toward zero marginal costs	Use of block chain technology in electricity sector
Decentralisation - more small-scale generation at local level	More engaged customers wanting greater say in energy choices
Implementation of microgrids	Electrification of loads (e.g. heating and EVs)
Reductions in cost of battery storage	Increased policy intervention in electricity markets
Improvements in battery capacity and performance	Increased competition in electricity generation and retail markets
Growth in the EV market and a push toward sustainable mobility	Emergence of capacity markets
Increased interconnection across regional or national transmission grid boundaries	Balancing markets operating across larger footprints (e.g. multiple regional grids, between countries)
Increased end-user adoption of microgeneration and storage technologies	New electricity system actors with focus on local and sustainable energy
Smart homes with "intelligent personal assistants"/machine learning for energy management	Technological changes occurring faster than policy and regulation can keep up
Grid defection (i.e. consumers going completely off grid)	Appeal of community grids and peer-to-peer interaction
Growth in the provision of demand side management services	Growth in IT capabilities (smart grids, smart cities) and the ability to collect, process, and respond autonomously to big data related to energy consumption, management and production
Step changes	
Renewable energy costs will fall to the point that they drive down the utilisation of fossil plants	Storage costs will reduce to a level that will completely change the nature of electrification in developing countries
We will see the roll out of grid scale storage solutions capable of	Storage deployment will rapidly accelerate following regulatory

serving entire cities	shifts that enable value to be recovered from multiple streams
Hydrogen solutions that operate from excess renewable energy capacity will become economical, offering cost-effective long-term storage and alternate supply	Home and community micro generation will become the norm with small users becoming self-consumers and only using the grid for balancing purposes
Roofing materials that are solar panels will become cheaper than conventional roofing materials and proliferate the market	New, non-traditional business models will evolve to provide services (such as comfort) rather than just energy
Distributed microgeneration and storage uptake will be rapidly accelerated by subsidies and other incentive mechanisms, price spikes in grid energy, or technological breakthroughs	Untapped 'customer side of the meter' opportunities will be exploited by the roll out of smart metering and associated tariffs and technologies
Individuals and organisations will be able to sell electricity direct to customers without the need to become a utility (e.g. through simple power purchase agreements)	There will be a change in methodology for charging for use of networks (e.g. to embedded benefits, constraint payments, capacity charges for domestic customers, etc.)
Renewable energy in grids will reach a point that forces electricity markets to completely re-evaluate their approach to wholesale bidding behaviour and regulation	A prolonged blackout (due to natural or man-made events) will shift political/consumer perceptions around resiliency and security of supply
Distribution network operators will take increased role in managing system balancing	The price of new EVs will become lower than that of an equivalent standard car leading to rapid EV uptake
Political changes will lead to reductions in research funding	Political changes will lead to additional research funding
There will be a reversion to vertically integrated utilities in order to support investment	There will be an unbundling of the incumbent utility to open up the space for new market players

Innovations

Cost effective inter-seasonal storage solutions	Fuel cell technology to relieve pressure on electricity system
Electricity storage for the grid that is five times less expensive than Li-ion batteries	Business models to support ethical investment and community enterprise in local energy solutions
Local energy markets that optimise energy use from consumer level up	Pricing mechanisms that account for real-time costs of energy and the peaks on the network and grid
A platform to deploy blockchain to enable peer-to-peer trading	Low cost loans for solar and storage
Pricing mechanisms based on power demand rather than energy	Strategic thinking and planned investments in electricity grids

Overhaul of the electricity sector governance processes to provide a whole-system perspective and make them agile and responsive to the significant changes emerging	In home heat storage to allow heat pumps to operate when generation/network capacity is available, but deliver the heat when it is wanted
Rapid expansion of the electrical grid transmission system, sited to bring wind into the grid	Standardised and easy to use smart management paradigms for home, neighbourhood, commercial and utility levels
Innovation in R&D and demonstration policy to facilitate cost reduction, support for clean technologies, and establishment of viability of low carbon strategies e.g. for heat	Regulatory changes (e.g. modernisation of the endangered species act) to support faster permitting processes for clean energy technologies
Standardisation of electricity markets and services across regions	Allowing multiple service providers at a connection point
Smart meter technology improvements	Affordable carbon capture and storage
Intelligent charging of electric vehicles to make better use of existing generation and network capacity	Mandates for environmental sustainability in markets through measures such as a global carbon tax
Conversion from methane to hydrogen for distributed gas systems	Innovation in clean electricity generation technologies
Access and use of multiple data streams related to energy system operation to optimise power flow through smarter control of supply side and demand side resources in both transmission and distribution grids	A holistic and comprehensive (rather than piecemeal) redesign of energy markets and network regulation to ensure they are consistent with a low carbon future (i.e. distributed low- or zero-variable cost generation, storage, demand side measures) in terms of market access, scale, and network complexity

The innovations participants believed would be mostly likely to occur include smart metering technology improvements; intelligent EV charging; and innovation in clean energy technologies. But the innovations anticipated to have the largest impact on energy systems include innovations in inter-seasonal storage, cost reductions in storage technologies, and holistic and comprehensive redesign of energy markets and regulation. According to one participant "*Efficient market design would make research into 'integration of renewable energy' largely redundant. The so-called challenges of integrating renewable energy are a symptom of poor market design, a failure to rely on efficient pricing, and the failure to develop efficient markets*." However, these three innovations with the greatest potential impact on electricity systems are also amongst some of the least likely anticipated to occur within five years.

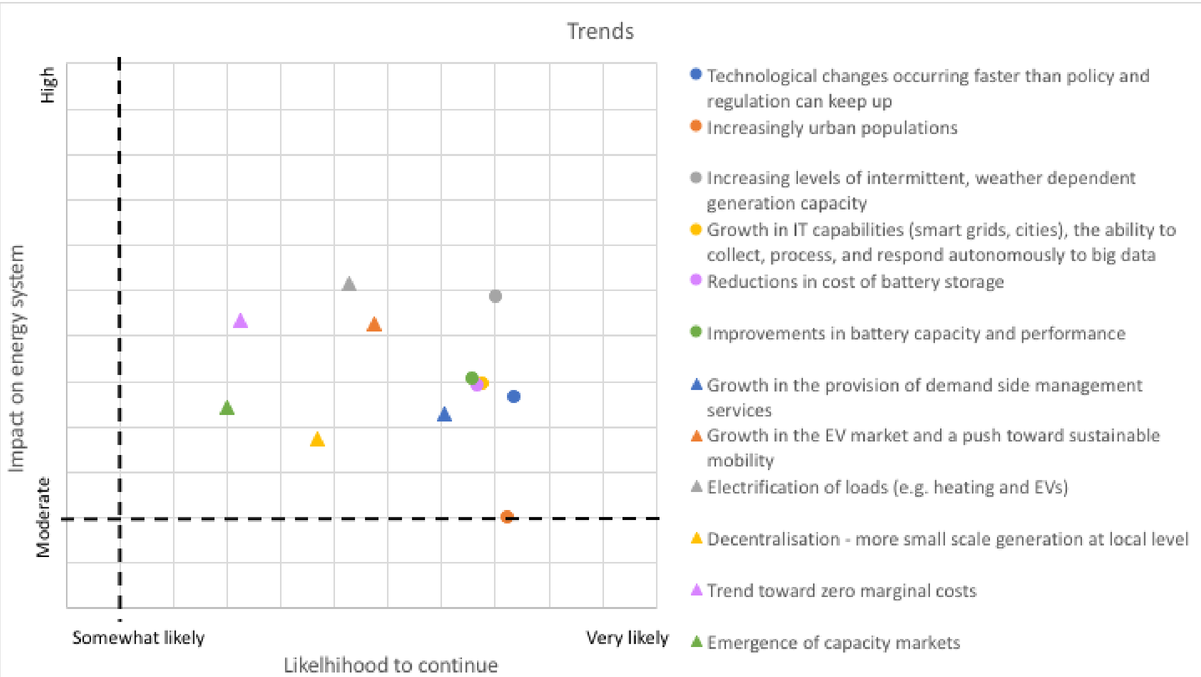

Figure 1: Trends most likely to impact energy systems

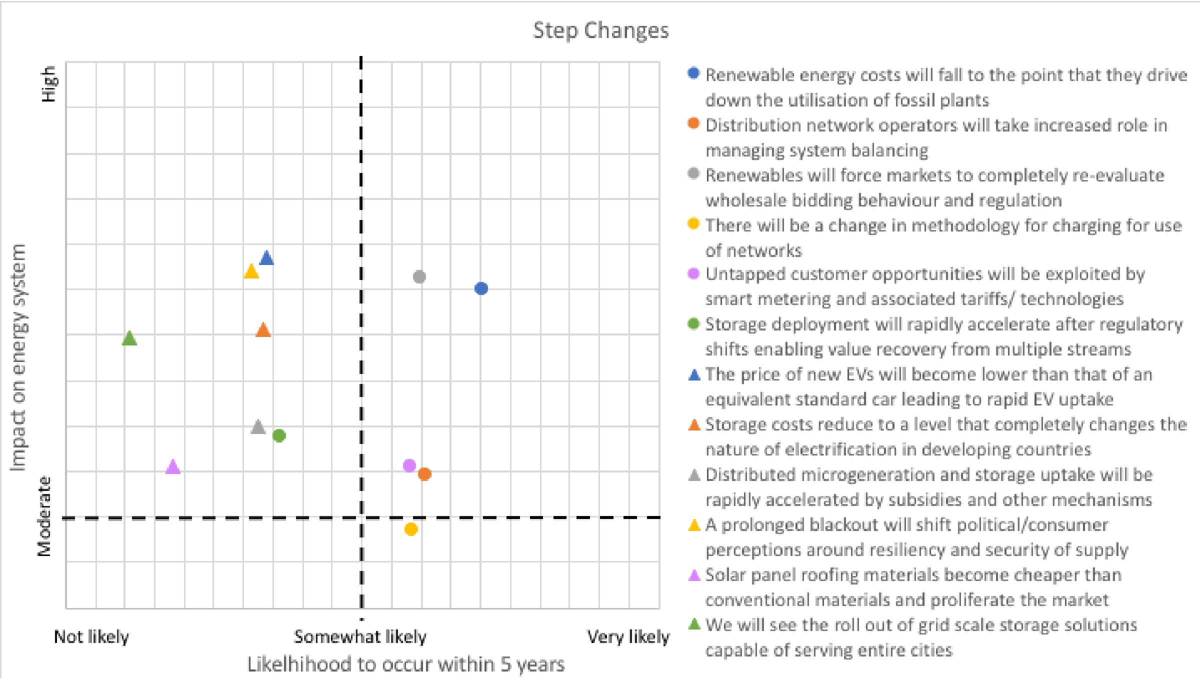

Figure 2: Step changes most likely to impact energy systems

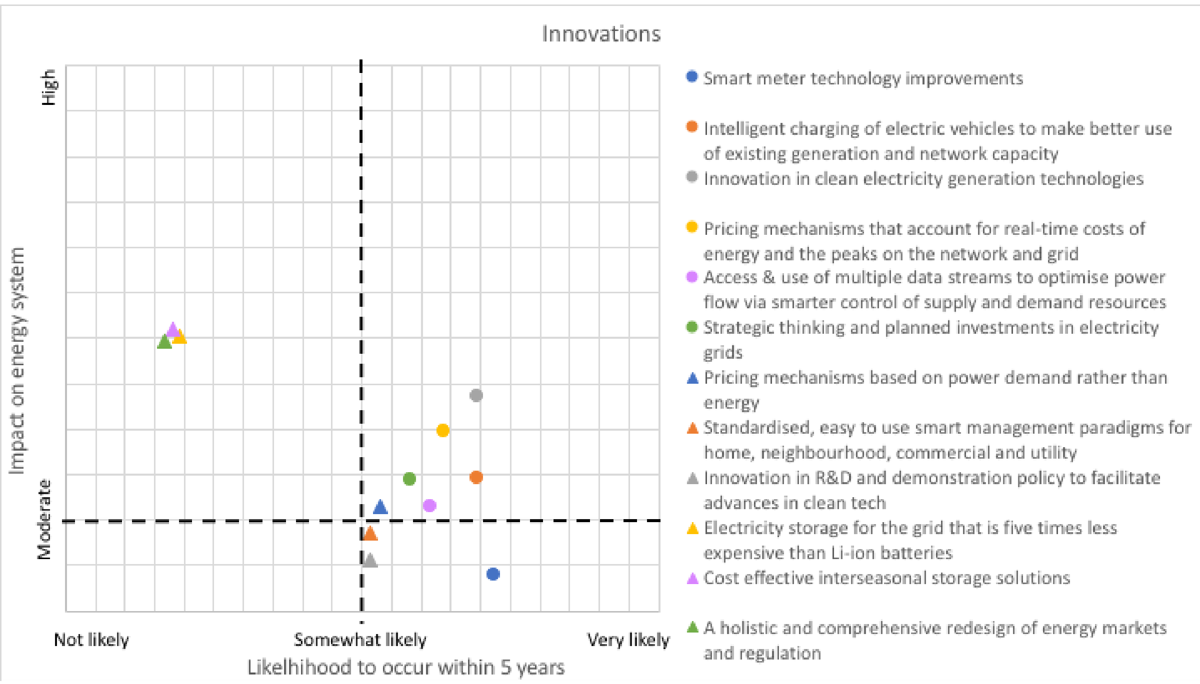

Figure 3: Innovations most likely to impact energy systems

It is also worth noting that two innovations were believed – fairly unanimously - to be relatively unlikely to occur within a 5-year time frame: conversion from methane to hydrogen for distributed gas systems; and affordable carbon capture and storage. While participants were fairly certain that these two innovations were unlikely to occur, there was much less agreement on their potential impact on the energy system, with these two innovations resulting in the largest variability between respondents (as compared to the other trends, step changes, and innovations identified) – see Figure 4. Perceptions of impact were independent of participants' geographic area of expertise or involvement with the energy sector (e.g. academia, policy, industry, etc.)

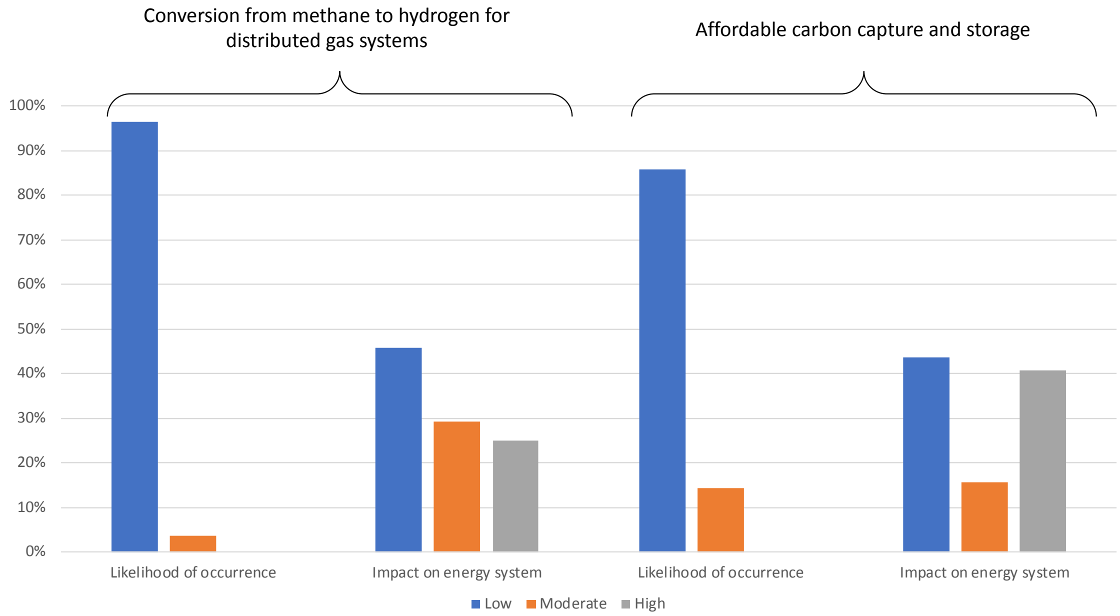

Figure 4: Innovations with low likelihood of occurrence

3.3. Determining key areas for intervention

Having established the trends, step changes and innovations participants thought could deliver the biggest impact on energy systems, the direction of questioning turned to exploring which of these potential areas of change could or should require intervention.

3.3.1. Supporting trends toward renewables

Of the 32 participants who responded to Round 3, 29 indicated that intervention would be needed to support trends around decentralisation, intermittency, and zero marginal cost issues associated with renewables to ensure that small scale renewable generation materialises in a "system-friendly" manner. While participants believed current trends would continue regardless, intervention could make it more strategic and effective. Five participants mentioned policy-based (e.g. incentives, net metering), planning (e.g.

incorporating resilience and climate action into energy policy and planning), and regulatory (e.g. standards for communication and co-ordination of distributed resources) interventions. Six participants believed markets needed to more appropriately value distributed generation, ramping services, firm capacity, inertia, and other ancillary services. Ten respondents identified the need for further research, modelling, forecasting, and demonstrations around technical, social, economic, and resiliency aspects of distributed generation.

Fourteen participants, from a variety of geographies (including Europe, US, New Zealand, UK) and sectors (including academia, government, industry, consultancy, NGO) believed intervention would be required to address issues arising from technological changes occurring faster than policy and regulation can keep up, and indicated the need for a review of regulatory frameworks and the development of new regulatory approaches. Interestingly, the two participants identifying as working in the regulation space did not note this as a key trend requiring intervention. Existing power sector governance and regulation is designed to cope with incremental evolution of technology, and whilst its processes are robust, they are inherently slow and bureaucratic. One participant outlined the need to avoid over-regulation, which can hamper implementation, and others suggested allocating government funds to enable regulators and experts to develop appropriate policies, making trends evident to doubters, policy responses accessible to decision-makers, and focusing regulation more on meeting goals and less on specific interventions. Governance and institutional arrangements need to change to address the transformational change occurring, going beyond technological changes to consider the whole system. This means involving a wide range of stakeholders including those introducing disruptive grid-edge technologies, and ensuring incumbent actors, technologies and mindsets do not preclude innovation. New governance frameworks will also need agility to cope with growth in requirements for code amendments / new codes, providing a framework flexible enough to keep up with rapid changes.

Twelve participants across a wide range of geographies and sectors thought the electrification of loads, including growth in the EV market, would require intervention to support the integration of renewables. Participants stressed the need for direct and indirect government support (especially to help new technologies get off the ground) as well as research to understand and support customer behaviour change. For electric vehicles, participants identified that extensive promotion will be needed, as well as regulatory mechanisms (e.g. for charging standards), financial levers, and policy support on issues such as charging points, road access, and parking restrictions for non-EVs. Participants discussed issues around the use of new loads, particularly to support flexibility. One participant believed that regulation would be needed to incentivise electricity use where it is most economic, and that new loads should be responsive to price signals, aligning use with times of low demand. However, another participant identified conflicting drivers to utilising flexibility, and outlined how reconciliation would be needed between network constraint management and maximising use of renewable generation. There is a need to better understand the limits of flexibility for new loads, and identify how markets, regulatory frameworks and governance structures can best exploit flexibility for whole system optimisation that meets the needs of different actors (including end-users and asset owners). Other research was also called for, particularly to consider how to address technical, economic and social factors associated with electrification and/or to ensure this change occurs, as well as research considering cross vector solutions (e.g. dual fuel heating).

3.3.2. Delivering step changes

Step changes most in need of intervention included: (1) renewable energy costs falling to the point that they drive down the utilisation of fossil plants (mentioned by 17 participants from academia, industry and government across a range of geographies), (2) re-evaluation of wholesale bidding and regulation (mentioned by 11 participants from regulation, academia and consultancy, mainly working in the US, UK, and New Zealand), and (3) distribution network operators taking an increased role in system balancing (mentioned by 13 participants from all sectors apart from academia, working mainly in the UK and US).

One participant indicated that renewable energy costs had already fallen to the point that they drive down the utilisation of fossil plants, and another participant mentioned that they believed this was happening in some places in the world and could happen quite soon in others. This poses a challenge for grid stability given that fossil fuel plants/back-up generators may be needed to fill intermittency, but which lack business models or other financial incentives to get up and running. Participants believe that long term investment signals are required, delivered through a capacity-based market, subsidies, carbon pricing, and other forms of market design to promote investment in renewables, storage, or demand management. Policy drivers were mentioned by participants, as well as policy streamlining to reduce soft costs (e.g. costs related to installation, permitting, marketing and sales) associated with clean technologies, especially solar. Regulation was noted by two participants, to help remove market obstacles to renewables, ensure system adequacy, support the phase-out of thermal power plants while providing employees future employment opportunities, ensure moderate retail electricity prices, and to ensure some transition for rapidly stranding assets. In addition to these measures, two participants identified the need for increased research, development and production funding to drive costs down further, increase attractiveness to investors, and identify how to economically incorporate renewables into the market while minimising risks from intermittency.

Eleven participants believed that the growth of renewables also meant intervention would be required to force markets to re-evaluate their approach to wholesale bidding and regulation. As one participant outlined *“renewable energy integration is already pushing many markets to new places, and the rapid increase of wind and solar may further push the market.”* However, if this transition is not thoughtfully planned there could be pain points with incumbents acting in self-interest and not in terms of the wider eco-system benefits, leading to stranded assets and unviable RD&D. For example, incumbents may demand complicated and unfavourable contracts from generators; delay the connection of renewable generation facilities via bureaucratic or ‘invented’ technical problems; make grid access difficult or very expensive; delay payments to generators or question their own obligations; charge excessive balancing costs; and withhold merit order savings by new renewables from consumers (Lauber and Sarasini, 2011). Some participants called for government intervention to deliver comprehensive energy planning, ensure competition between market actors, and ensure prices reflect system value (including the locational value of generation as decentralised generation and storage become increasingly common). Other participants called for further research to value flexibility, and explore what new wholesale bidding behaviour and regulation might look like, how wholesale market behaviour might change, and identify competitive vulnerabilities.

The third step change related to the emerging role distribution network operators may play in system balancing. System balancing in distribution networks is likely to become a bigger challenge as more renewables are added, but the precise scope of the future distribution system operator (DSO) and how they will interface with a (more independent) system operator (SO) remains uncertain. Localised system balancing as well as, or in addition to, active network constraint management is not yet established, and research is needed to explore system operation at the distribution level, impact on the wider system, and the role of the DSO. Additional research in the impacts of increased distributed generation penetration, particularly in areas of network stress will be valuable, as will a greater understanding of the effect of end-user engagement on system operations. Simulations of different scenarios could help DSOs anticipate their future role, and improved information technology will support local forecasting and system balancing.

3.3.3. Driving innovation

The top innovations identified in the Round 2 survey clustered into three main categories. The first relates to the market and regulatory framework changes needed to ensure consistency with a low carbon future, and includes:

- a holistic and comprehensive redesign of energy markets and regulation, highlighted by 8 participants with geographic expertise in the UK (3), US (4) and Europe (1)

- strategic thinking and planned investments in electricity grids, noted by 11 participants with geographic expertise in the UK (4), US (3), NZ (3) and Eastern Europe (1)
- new pricing mechanisms, mentioned by 12 participants with geographic expertise in US (5), Europe (3), NZ (2) and the UK (1).

Findings show that despite differences across geographic areas, including different rates of progress, policy approaches and regulatory frameworks, there was consensus that intervention was urgently needed to deliver strategic thinking and redesign policy, market, regulation and pricing structures.

Participants identified that existing market and regulatory frameworks are the result of incremental power system evolution, and while they have delivered pragmatic and effective solutions to date, the current energy transition requires transformative rather than incremental change. This is due to increased complexity from new grid and grid-edge technologies and the emergence of new actors and business models leading to an urgent need for new technical and market functionality, which is unlikely to be delivered under existing regulatory, market and governance arrangements. A greater understanding is required to identify net benefits, winner and losers, the role for incumbents, and the future for existing assets and new investments.

Many participants believed further research is required into alternative market models, including specifications for how enabling frameworks that can deliver transformative (rather than incremental) change would operate. They also discussed the role for carbon markets as well as existing energy and capacity markets; costs and pricing implications in shifting to maximum demand pricing alongside pricing for energy units; flexibility tariffs; and mechanisms that bundle transmission, distribution, energy market, and ancillary service prices into a delivered real-time price to the end user. Participants believed that more consistent and long-term policy strategies would be required to send appropriate long-term investment signals, such as investments in transmission network expansion to bring more renewables into the market. They also outlined the need for change to be led by government and regulators (consolidating dispersed interests), supported by the academic community and industry, to deliver broadly accepted frameworks and processes.

The second main area relates to innovation in clean energy technologies, particularly:

- clean electricity generation (which could lead to cheaper power, higher returns on energy production, and maybe a completely new way of delivering power) mentioned by 12 participants with geographic expertise in Europe (2), UK (2), US (5), Africa (1) and New Zealand (1)

- cost effective storage (including inter-seasonal) solutions (which could provide a massive catalyst for structuring a new and cleaner energy system) mentioned by 9 participants with geographic expertise in the UK (4), US (2), New Zealand (1) and Africa (1).

Participants mentioned a range of different technologies, including bioenergy, small modular nuclear reactors, lower cost wind, clean coal, carbon capture and storage, flow batteries, and zinc air batteries, and outlined that the focus should be on delivering low carbon, economic and dependable power to the grid. However, they also believed that more technological research would be required to develop solutions, and government intervention (e.g. subsidies, market incentives, polices) would be needed to deliver these and remove risks from early stage R&D.

The third key innovation area requiring intervention is related to smarter network management, including:

- the use of multiple data streams to optimise power control in grids, mentioned by 10 participants with geographic expertise in New Zealand (2), US (4), UK (4), and Europe (2)

- intelligent charging of electric vehicles, mentioned by 13 participants with geographic expertise in US (4), Europe (3), UK (4), New Zealand (2)

- standardised and easy to use smart management paradigms for home, neighbourhood, commercial and utility levels, mentioned by 4 participants with geographic expertise in US (2), UK (2)

Participants outlined the need to create a roadmap for how information can be mined and used to improve decision making activities. Further R&D into systems than enable a "decentralised, responsive, EV friendly grid that has greater democratic input while being able to provide security of supply" and avoid "system shocks (e.g. mass switching of appliances causing potential frequency excursions and even system collapse)" is required. Improved sensors and controls may be needed, and interoperability will be a key element as multiple data streams will have to be coordinated and integrated, all the while ensuring data and cyber security. One participant outlined the lack of a system architecture to deliver this, making it a priority area for R&D. Another participant outlined the need for government to take a more active role in planning and delivering energy policy that supports the integration and use of data streams. Intelligent charging of electric vehicles, including vehicle to grid technology, provides an interesting use case in which end-users must be engaged, and further research is required to explore issues around battery life, revenue streams, usage patterns (i.e. so recharging patterns and frequency can be better predicted), and EV owner flexibility (i.e. to what extent they are prepared to relinquish control and at what price point). Finally, standardisation (e.g. around communication systems) will be key to enabling different data streams to be *integrated* and *used* to optimise energy flows.

4. Discussion

While this study did not identify a single vision of what a future net-zero energy system would look like there was consensus that renewables would play a much bigger role, drive down the utilisation of fossil fuel generation, and impact electricity market operation. Electricity systems are likely to become more decentralised, and new demand side technologies (e.g. storage, EVs, heat-pumps) could see homes and businesses becoming active energy participants. Decentralisation will also place more emphasis on distribution network operators taking an active role in local system operation and balancing.

New approaches will be required to manage increasingly decentralised, multi-vector energy systems. This includes IT and data driven smart grids capable of intelligently and autonomously optimising networks and assets. To drive optimisation, pricing mechanisms that account for real-time (and environmental) costs of energy generation and network capacity will be required. In turn this may require market and regulatory reform.

Sustainable hydrogen and carbon capture and storage, whilst relatively unlikely to manifest within a 5-year time frame, could nonetheless prove disruptive to how future energy systems develop. For example, hydrogen availability could affect transport and heating and cooling decarbonisation pathways by complementing or substituting electric vehicles and heating systems.

While there was some uncertainty around which technologies would prevail in future electricity systems, the key message emerging from the study was the need for a rapid transformation of policy, regulation, markets, pricing, and governance. Participants were clear that the challenges did not lie with the technologies, but rather with delivering an aligned vision, supported by institutional structures, to incentivise, facilitate, and de-risk the delivery of a completely different type of electricity system. The following sections discuss these issues further.

4.1. Visions and leadership

Participants indicated that a number of trends, such as increasing penetration of affordable renewable power, energy storage, electric vehicles and decentralisation, will happen whether or not governments, policymakers and regulators desire it. This entails substantial energy system transformation and could be disruptive, even chaotic, if unplanned or unexpected. Participants outlined a range of measures that could comprise a ‘vision’ for “system-friendly” energy system transition, including:

- Price signals to appropriately value externalities (such as greenhouse gases), distributed generation, demand-side technologies and approaches (e.g. storage, demand-side management) and smart grid operation and balancing
- New markets and approaches to policy and regulation to enable smart local energy systems to emerge
- A transition to IT and data-led smart energy systems
- The emergence of new actors and a change in responsibilities for incumbents

Future electricity system 'visions' will be place and context specific, thus any lessons from this study will need to be translated into local context. However, at a high level there was consensus that more consistent and long-term strategies and signals would be needed to send the right signals to investors, and this should be led by government and regulators working with the academic community and wider industry to consolidate dispersed interests and provide an aligned approach. Specific measures are discussed in more detail below..

4.2. Price signals, incentives and market reform

Future electricity systems dominated by zero-marginal cost variable output renewables cannot operate on the same basis as traditional, centralised, fossil-fuel led electricity systems. Future systems will need to value renewable (including distributed) generation, balancing and ancillary services (including firm capacity and managing inertia) and incentivise smart grid operation (including, for example, maximising local consumption).

Participants outlined the need for a holistic and comprehensive redesign of energy markets and network regulation to ensure they are consistent with a zero-carbon future in terms of market access, scale, and network complexity. Innovative measures, including more strategic thinking around investments and shifts in pricing mechanisms will be important across a wide range of geographies to deliver on the goals of the Paris Agreement while ensuring power systems remain reliable.

Markets will have to evolve to support the shift toward distributed variable renewable resources with high capital and low- or zero-marginal costs. The existing market paradigm - namely that short run marginal costs can be used to rank despatch priorities - will become increasingly irrelevant, and trading windows may have to shift closer to real time to more effectively incentivise the use of renewables.

It will also become important to consider how markets provide long-term investment signals to developers, asset owners, and utilities, especially as penetration of renewables and corresponding frequency of zero-price hours of electricity increases. In recent years this has seen the emergence of capacity markets in some nations, which aim to tackle issues related to investment recovery, system adequacy, and security of supply, although their effectiveness in different jurisdictions varies.

4.3. Governance for smart and local energy

Institutions will need to evolve to support two emerging trends: (1) increasing prevalence of cyber physical and “smart” systems, and (2) incorporation of local actors and the diversification of roles and responsibilities.

4.3.1. Smarter energy systems

IT and data enabled ‘smart grids’ are a key enabler of energy system transition, offering the possibility of optimising more complex local and national energy systems. However, this requires multiple data streams to be available, devices (such as distributed generation and electric vehicles) to be visible, and the enabling sensors, IT and control technology to be available, tested and integrated. With increasing digitalisation of energy systems, interoperability and cyber security become critical factors. Standardisation or convergence (e.g. around communication systems) is key to enabling different data streams to be integrated and used to optimise energy flows. Novel system architectures using multiple data streams to optimise across a range of temporal and spatial scales need to be developed, making this a priority area for R&D.

Opportunities provided by more granular data and more complex control must be considered holistically; as well as supporting operational system optimisation, “smart” energy systems also provide enabling capacity for other aspects of the transition including technical operations, value propositions, and business models. This may require government to take a more active role in setting the vision and governance structures for delivering a future-proof digitalised energy system.

4.3.2. Local actors and diversification of responsibilities

The anticipated energy system transition seems set to engage more actors at local scales, including end users. Shifts in opportunities to access value on both the supply and demand side makes it increasingly important to rethink market design to level the playing field for all actors. Although political will may be limited, and there may be resistance from powerful incumbent organisations, holistic changes to markets and network regulation could see the unbundling of utilities opening up the space for new actors. If they can overcome market entry barriers, this could see a rise of new electricity system actors with focus on local and sustainable energy, giving rise to new business models that support the changing nature of electricity end-users. While willingness from Government and industry could present a major barrier to action, there could also be political recognition in creating new rules appropriate for a decentralised and democratised electricity system. Such a major redesign would also require significant intellectual capital and regulatory support to deal with the associated complexity. This raises questions around leadership, and the lack of clarity around who could drive the transition, including overhauling current market and governance arrangements to deliver a system more able to cope with the rapidly transitioning sector.

New business models will be required to deal with the increasing number of system actors and complexities, particularly to optimise bi-directional electricity grids in a way that is attractive to all consumers, including prosumers. It is important to incentivise consumers to remain connected to the grid, as they go off grid it could lead to challenges around paying for the fixed costs of energy infrastructure. In essence wealthy prosumers might disconnect leaving poorer consumers to pay for the grid. It is important for policies to refrain from focussing only on prosumers and risk neglecting vulnerable customers.

4.4. R&D and knowledge

In discussing interventions to promote trends, step changes, and innovations toward renewables, the need for additional research was mentioned 55 times, including technical research (e.g. new storage technologies), social research (e.g. adoption and use of new technologies), research on markets and regulation (e.g. shifts in wholesale bidding behaviour and regulation), and research around impacts (e.g. localised emissions reductions). There is also need for whole system research (e.g., energy system operation across vectors), and to model and manage extreme scenarios and their implications (e.g. black start scenarios and policy implications).

A second related discussion focussed on research, development and demonstration to facilitate cost reductions and innovation in clean energy technologies, and establishment of viability of low carbon strategies, e.g., decarbonisation of heating and cooling. There are barriers, largely due to the lack of favourable regulatory frameworks, and risks of funding reductions resulting from political changes (and the desire for re-election). However, one participant mentioned that government commitments (e.g. to a credible 5th carbon budget in the UK) could be a key enabler along with favourable funding/tax arrangements.

The third discussion around R&D and new knowledge related to the workforce, who lack skills to support the energy transition and manage the emerging energy landscape. This is already a significant challenge - with a potentially less stable geopolitical landscape, and a Brexit impact (in the UK) on freedom of movement, coupled with the UK simply not generating enough home-grown engineering talent - managing a complex energy system in today’s environment will become extremely difficult. In a future, more complex energy landscape, engineering will be a critical national resource – yet, according to one participant, one which is underinvested in and takes a long time to build.

5. Conclusion and Policy Implications

The pace of change is an important consideration arising from this work. Many of the trends outlined by participants are already manifest and the pace of change expected to increase over the next five years. As such near-term decisions to both support (e.g. facilitate technology roll out at a rate commensurate with targets) and manage (e.g. implement changes to market design and deliver smarter grids) are imperative. It is a critical window for policy action.

5.1. Policy Implications

Alongside the rapid pace of change policy makers must account for, there remain multiple uncertainties on how specific solutions will work together to deliver a highly renewable, net-zero electricity system. Any decisions made now may need to be adaptable to future disruptions. An important consideration within this is how to soften the blow for those businesses and technologies that will effectively be replaced by this transition. Failure to do so could result in incumbent drag. Some decisions, such as on the strategic role of hydrogen and / or carbon capture and storage, appear longer-term. However, if these approaches feature as a key component of future energy strategy, such as is the case in the UK net-zero target, it may be necessary to adopt policies to accelerate them, aligning future long-term visions with more immediate strategies and policies to deliver them.

Clearly there is a role for government and relevant institutions in zero-carbon transformations. Participants discussed the need for decisions and steer on a number of strategic issues, initially on big picture areas such as future energy vision, but also on issues such as market structures, energy pricing and smarter network operation. In effect these decisions serve to reduce uncertainty for energy system actors and consequently support investment through mitigation and / or reduction of key risks (e.g. wholesale and pricing reform to give certainty on future revenues for zero-carbon generation).

Linked with the previous point on decisions, there is also an issue of how future energy systems will be governed. Participants alluded to futures with an explosion of technologies and actors, including substantial new activity at the local level. This indicates several issues. First, there is a role for policy in creating space for new actors and energy business models aligned with futures energy visions to emerge; aligning vision with strategic innovation. In the UK, Ofgem's regulatory sandbox is an example of a niche created to allow business model experimentation (Ofgem, 2018). Second, given that participants expected significant decentralisation of energy systems, there may need to be commensurate decentralisation of policy and regulatory functions and institutions, while maintaining alignment across scales to deliver on national or centralised future energy system visions. Third, new governance issues are expected to emerge in a data- and IT-led future energy system, these include data protection and cyber security.

Finally, support for innovation and skills will be required. Participants clearly outlined a vision for future systems where new technologies and business models emerge, potentially replacing incumbents. There is a clear role for government and related institutions to create an environment where research, development, demonstration and deployment can work in an aligned manner to deliver technologies, system integration and business model innovation at a rate commensurate with zero-carbon energy systems. Alongside a transition in the skills required is an important component of zero-carbon education and immigration policy. This includes consideration of re-skilling those whose jobs are displaced in the transition (e.g. mechanics working on internal combustion engine vehicles).

5.2. Concluding remarks

This paper set out to explore the trends, step changes and innovations that could impact the integration of renewable energy into electricity systems, stimulating cross sector engagement on key issues and exploring policy implications. The 3-stage Delphi study captured insights from over 60 participants with expertise from a variety of countries around the world, providing good geographical diversity. In the first round the 61 respondents came from a variety of sectors, however, the second round was perhaps a little over-represented by academics/researchers and lacked representation from community energy groups and regulators. While drop off is anticipated between rounds, the findings – particularly from round 2 during which prioritisation of trends, steps changes, and innovation occurred – may have been skewed by this distribution of respondents.

Furthermore, while the study explicitly sought respondents from across the electricity sector to address the question around integrating renewables, the findings highlighted the need for more joined up, whole systems thinking that may extend beyond the traditional energy sector. For example, some participants identified the potential impact from new roofing technologies, block chain development, big data and smart cities, urbanisation, and new business models such as “comfort as a service”. This illustrates how the electricity system is inherently interconnected to the wider economy, and as a consequence the range of participants’ expertise sought for this study may have been too narrowly focussed on the electricity sector. Furthermore, the future may see increased cross-vector approaches to energy system decarbonisation, extending beyond the integration of renewable energy into electricity systems, and focusing on integrated approaches across power, heat and transport, to enable whole system transition. In this case future work may benefit from considering the wider challenges related to delivering a net-zero energy system rather than focussing on each vector independently.

Findings showed that participants believed a zero-carbon electricity system to be plausible, either through 100% renewables coupled with storage and demand response, or base-load nuclear, biomass, or carbon capture generation. While there were discussions around the viability of various technologies that might underpin this (e.g. chemical storage solutions, affordable carbon capture and storage, methane-to-hydrogen), the key challenges were not technological. Instead, they revolved around the creation of a sector wide vision, supported by aligned policies and strategies commensurate with required pace of a net-zero energy transformation.

Intervention was considered necessary to address these big picture issues, which include a transformation in market structures, energy pricing and network operation. However, there was a lack of clarity around who could deliver this vision, given the increasing diversification in roles and responsibilities for energy system planning, management, and operation. Leadership, which was considered necessary to support change, would require an overhaul of market and governance arrangements to create an institutional framework more able to cope with the rapidly transitioning physical system.

This work considered a five-year timescale, which demonstrably set a boundary around the technological and institutional changes that were discussed. Innovations reducing costs of storage technologies were believed most likely to have an impact on the energy system but less likely to occur; carbon capture and hydrogen were believed unlikely to occur at all; and inertia in policy making, governance and market and regulatory frameworks were anticipated to reduce the impact that other advances could make. Future work would benefit from looking across a range of time scales, exploring actions required in the short, medium and long-term, and the differences in uncertainties surround them.

Another challenge that emerged relates to the differing levels of specificity across trends, step changes, and innovations identified by participants. For example, the step change “Renewables will reach a point that forces markets to completely re-evaluate wholesale bidding and regulation” is relatively broad compared to “Distribution network operators will take increased role in managing system balancing” or “The price of new EVs will become lower than that of an equivalent standard car leading to rapid EV uptake”. Although it’s not clear that these different levels of specificity affected prioritisation in Round 3 (in which both general and more specific measures were prioritised), there may have been some ambiguity in how participants interpreted more generalised statements, which may have affected their suggestions for interventions. Throughout the Delphi study we tried to ensure statements accurately reflected the issues raised by participants, but further work may benefit from a more detailed exploration of the varying interpretations around less specific trends, step changes, and innovations, and the corresponding interventions required to address them.

Further work could also explore how participants perspectives differ according to their positioning within the sector and their geographical location and the wider context within which their energy system is situated. While this work has been particularly illuminating in highlighting consensus between experts working across different parts of the sector (industry, government, regulation, academia, etc.) and across a wide range of geographies, we were not able to deconstruct responses according to these variables.

Finally, given the current global situation created by COVID-19 and its impact on the energy sector more broadly, it would be useful for future work to consider how the energy system transition is situated within the wider global context.

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