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Transforming the grid for a more environmentally and socially sustainable electricity system in Great Britain is a slow and uneven process

Matthew Lockwood[a,1]

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Electricity system decarbonization is key for environmental sustainability. From a consumption–production perspective, much attention has been paid to changes in how electricity is generated and used, but electricity systems also rely on a grid infrastructure that connects and integrates production and consumption, and which will also need to transform. At the same time, new technologies in the electricity system, including the grid, offer the potential for more socially sustainable ways of producing and consuming energy. However, in practice, change has been slow, uneven, and often dysfunctional. A socio-technical transitions approach offers insights into why this is so, seeing electricity system change not simply in technical and economic terms, but also as the outcomes of interactions between technology and social and political processes. The approach draws attention to the particular challenges of achieving rapid transitions in complex critical infrastructures like electricity with strong institutional logics of security. This article applies this approach to the case of Great Britain, where despite strong commitments to sustainability in the form of high-level climate policy, the electricity grid has often been a constraint on the pace of change. The nature of the British transition is explained partly by weak links between these high-level goals on the one hand and the detailed rules and practices in the electricity system on the other. It is also explained by patterns of ownership and grid regulation in the British case that protect incumbents and make it difficult for new actors to develop the system in more socially sustainable directions.

electricity infrastructure | institutions | sustainability transitions

Significance

Electricity grids are located in socially constructed systems of rules and relationships, so full understanding of grid transitions requires a broad range of social science approaches to complement technical perspectives. Rapid transformation of electricity systems to greater environmental and social sustainability will require reforms to regulatory institutions and sometimes ownership, changes in institutional logics, and good alignment between the electricity grid rules and the wider policy context. Governments and civil society are likely to be key change agents.

Electricity has played a central role in the creation of the two intertwined trends—rapidly increasing human well-being and increasing environmental degradation—that have produced the Anthropocene (1). Many electricity systems are still heavily based on carbon-intensive fossil fuels (2), so the decarbonization of those systems can make a key contribution to reducing greenhouse gas emissions, as well as other forms of pollution. From a consumption–production perspective (3), much attention has been paid to changes in how electricity is generated (e.g., renewables) and increasingly to changes in how it is used [e.g., electric vehicles (EVs)] (4). But electricity systems rely on a grid infrastructure that connects and integrates production and consumption.

To facilitate the low-carbon transition, especially without incurring huge cost increases, electricity grids will also have to undergo significant changes in design and operation (5, 6). However, transforming these systems in practice is often a slow, difficult and uneven process. A socio-economic transition approach can offer insights into why this is the case. It frames transitions not simply in technical and economic terms, but also as the outcomes of interactions between technology and social and political processes, with associated actors, institutions and interests (7, 8).

The growth of renewables, especially solar photovoltaic (PV) and wind, as key low-carbon technologies represents a number of challenges to the traditional electricity grid. One is that the grid in most countries has been built to connect existing fossil fuel, nuclear and large hydroelectric power plants, but these are often not in the same locations as the best solar and wind resources. A second is that wind and solar PV produce electricity intermittently, i.e., depending on weather conditions. Managing intermittency will require a more flexible electricity system, but one where the sources of flexibility are low-carbon, including batteries and the ability to vary demand [sometimes known as demand side response (DSR)] (9).

Wind and especially solar PV can also be small-scale and modular, sometimes work best in a decentralized way, connected directly to low-voltage distribution networks. Because these networks were not built for generation, rapid investment in solar and wind can quickly come up against local constraints. Again, flexibility through batteries and

Author affiliations: [a]Science Policy Research Unit, University of Sussex Business School, Brighton, UK, BN1 9SN

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[1]Email: m.lockwood@sussex.ac.uk.

DSR can help manage such constraints cost-effectively (10), but realizing their potential requires a transformation of distribution grids to handle bidirectional power flows and better management of generation and loads (3). Digitization of the grid through ICTs, with improved ability to remotely observe and automatically control power flows and to anticipate faults, is an essential part of this transformation (5, 11, 12). Through these capabilities, distributed renewable generation, batteries (including in EVs) and DSR [collectively called "distributed energy resources" (DER)] could be integrated and optimized to balance production and consumption, minimize costly demand peaks and maximize the use of networks (13). This "smart grid" vision (14) breaks down the traditional distinction between producers and consumers of electricity, with fuzzier boundaries to the grid as millions of devices in homes and businesses will play functions in the system. Smart grids also offer improved security, resilience and quicker restoration of electricity after storms (13, 15).

Taking these anticipated changes together, some observers talk in terms of the three "D"s, i.e., decarbonization, decentralization and digitization (16). Such changes will be needed for greater environmental sustainability of electricity systems. However, the development of modular renewable technologies and the potential of small-scale DSR opens up the possibility of new active roles in grids for actors such as households, community groups and other new entrants, beyond the traditional incumbent large utilities. Whether and how far this happens depends on access to and control over energy resources (17), which are clearly important for the *social* dimension of sustainability (1). This agenda is sometimes expressed in terms of adding a fourth "D," i.e., *democratization*.

Below I use the socio-technical approach to explore the grid transition in the case of Great Britain.* Grid transition is a part of the wider process of change in the country's electricity system discussed by Pearson and Watson (18) in this Special Feature. Britain is an illuminating case because despite strong political consensus on climate change, emission reduction targets and policy for renewables expansion, the electricity grid has often been a constraint on the pace of change. This case also shows the challenges in making electricity systems more democratic and inclusive.

A Socio-technical Transitions Approach to Electricity Grids

Transitions scholars are concerned with the movement from one stable consumption–production system to another, where such systems are conceptualized as complex structures across a range of different areas including industry, technology, politics, and society (19). In explaining how transitions are possible despite system stability, the multi-level perspective (MLP) framework uses the concepts of "regimes," "niches" and "landscapes" (19). The regime constitutes mainstream ways of realizing various social functions, incorporating formal and informal rules, practices and skills, including those of technology users, embedded in institutions and infrastructures (20). It generates a "selection environment" for existing and new technologies, business models and social practices. Change and innovation can occur from within regimes but tends to be incremental in nature. By contrast, radical innovations of the type usually associated with major transitions are generated in niches. This is where radical novelties are nurtured and developed, producing technical innovations that offer new ways of satisfying social demands (21), often alongside new business models. Both regimes and niches are situated in a socio-technical landscape, comprising deep structural trends. It is pressures from landscape developments, such as the recognition of climate change, that create opportunities for technologies developed in niches to break through, enter the mainstream regime and potentially transform it (19, 20).

Within this approach, infrastructures have specific characteristics that shape the nature of the transitions they go through (22). Because infrastructure systems are large-scale, capital-intensive and have a long life cycle, they tend to have a high degree of path dependence. Large sunk costs, continuous societal dependence on infrastructure services and the difficulty of shifting suddenly to a new architecture makes radical transformation risky, so there is a greater tendency towards incremental change than in many other socio-technical regimes. Complex distributive and networked infrastructures with many inter-related elements, such as electricity, are particularly prone to lock-in.

Electricity infrastructure has some additional particular features relevant for transitions. As critical infrastructure, it is highly institutionalized with formalized codes and rules (23), and a strong institutional logic (24) of security. Grids are also seen as having monopoly characteristics, meaning that they are often state-owned. Where they are privatized and run by network companies, these are regulated (25). Historically the goals of regulation have been economic efficiency and security of supply. Because of these arrangements, niches for innovation in grids cannot be developed by new entrants as in normal markets, but must be created and managed by regulators and regime incumbents themselves, against the grain of the institutional logic (7, 26). The recognition of this fact has led to calls for new forms of regulation to encourage innovation for smart grids (13, 27) and distributed generation (28).

Results

The UK privatized its state-owned electricity system in 1989. Generation, grids and supply were all separated from each other. New privately owned transmission and distribution companies were created, along with an electricity regulator (later merged with the gas regulator to form the Office for Gas and Electricity Markets, Ofgem). Evolving out of pre-privatization structures, there are six large distribution grid companies owning 14 regional networks, each typically serving several million households. Most distribution companies are now owned by infrastructure banks and funds seeking a combination of low risk and steady returns.

The approach to grid regulation in Britain was shaped by a wider economic policy paradigm that emphasized the role of competitive markets. Applied to the regulation of monopoly networks, this meant creating incentives for efficiency, rewarding companies if they could deliver savings on their projected costs for investing in networks (7). This approach had immediate effects through the 1990s as costs and network charges for electricity consumers fell, mainly achieved through shedding labor and cutting back on investment.

However, even as the privatization revolution was settling in landscape pressures were building, with the imperative to decarbonize electricity growing from the 1990s onwards. An important part of decarbonization to date has been due to developments that did not have major implications for grids, especially the building of gas-fired power stations in the 1990s (18), and the subsequent use of these plants to displace coal plants in the 2010s (29).

By contrast, other aspects of decarbonization, especially the growth of renewables, did increasingly require changes to the grid. But the relationship between climate policy as a landscape pressure

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*Northern Ireland has its own separate energy regulator, and its electricity system is significantly integrated with that of the Republic of Ireland, so this article mostly refers to Britain rather than the UK.

and the grid infrastructure sub-regime has often been unclear and unpredictable. The UK has legislated five-yearly carbon budgets, but these are economy-wide. Until very recently there has been no specific decarbonization target for the electricity system. The UK did adopt targets for the growth of renewable energy under an EU directive in 2001 (although there was no specific target for renewable electricity) and new policies drove the expansion of onshore wind from the mid-2000s onwards (Fig. 1). However, nuclear power was taken off the policy agenda in 2002 but came back on it in 2006. Deployment support for solar PV was expanded in 2010 but almost completely cut back in 2016, while onshore wind was effectively banned at the same time. Meanwhile, offshore wind was massively scaled up from the early 2010s. Deployment support for demand-side technologies like EVs and heat pumps has been subject to sudden, often unannounced changes. Uncertainty in the direction of wider policy has often presented a major challenge for the regulator and network companies, who have had to second-guess future trends in generation and demand, or have tended to lag behind policy shifts. Finally, the alignment between policy goals and regulatory institutions has been weak. The basic remit of Ofgem as electricity regulator was to deliver efficiency and system security. While this remit was tweaked to reflect policy goals of sustainability over the course of the 2000s several times, it was not until 2020 that it published a decarbonization action plan.

Early changes in the grid regime arose because the best wind resources were to be found where existing networks were weak or even non-existent, especially in the north of Scotland. Transmission network regulation required reinforcement before projects could connect, and a large queue of potential projects had built up by the late 2000s. The grid bottleneck threatened to undermine the expansion of wind and reaching the renewables target. Actors in the grid infrastructure sub-regime were not able to agree a solution, and eventually the government had to step in and force a rule change in 2010, allowing wind projects to connect first, with the transmission grid operator then having to manage any resulting congestion.

This experience led the government to recognize that major changes required to accommodate the growth of wind could not be handled within business-as-usual regulation. It was increasingly realized that resulting growth in wind generation in Scotland would require more capacity in connections to England, where most demand was located (30). Some argued for increasing capacity through smarter approaches using existing infrastructure (31), but the National Grid transmission network owner lobbied the government hard and ultimately successfully for building new transmission lines.

Around the same time, the government also prompted the regulator to adopt a new framework for grid infrastructure to connect offshore windfarms to the transmission grid. This framework, allowing competition in the provision of network links to the onshore grid, is important because as costs have come down sharply over the last 10 y, large-scale, transmission-connected offshore wind is likely to play a central role in the future British electricity system.

However, this system will also involve renewables connected to the lower-voltage distribution networks. Over the course of the 2010s, distributed generation capacity more than doubled from 15GW to almost 35GW, growing from 16% of total capacity in 2011 to more than 30% in 2018, driven mainly by a boom in solar PV (32). While a little under a million rooftop solar systems were in place by the end of the 2010s, the vast majority of capacity growth was in commercial schemes of 50 kW and above (Fig. 2).

The scale-up of distributed generation posed capacity problems for networks designed principally for consumption. Historically, regulation rewarded distribution network companies for solving problems like these by reinforcement—larger wires—rather than by smarter solutions such as contracts with suppliers of flexibility. Network companies earned more money the greater was overall demand, encouraging a larger rather than a smarter grid. They were penalized for system security failures, and so tended to avoid any innovations at scale that might involve risk (33). They also had incentives to focus on activities that could save money within a few years, rather than think about the long-term transformation of the grid through innovation (5, 7, 33). The result was a low-risk, capital-intensive sector with little capacity for innovation. As late as 2010, a senior figure in Ofgem acknowledged that the way grids were designed, built and operated had not changed significantly in 50 y (26).

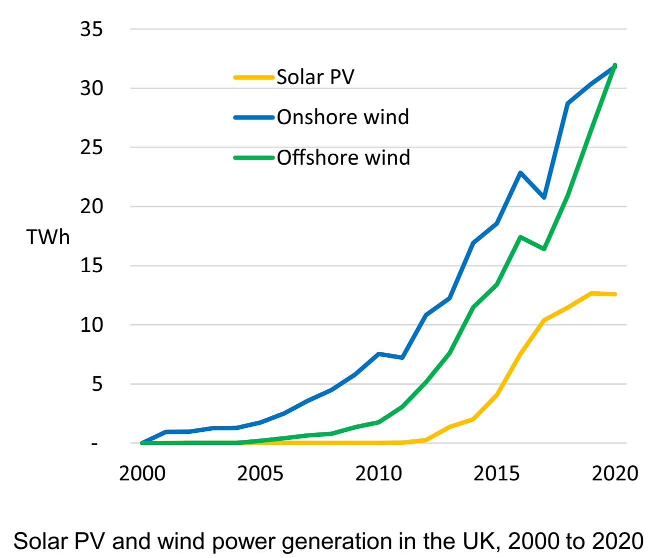


Fig. 1. Solar PV and wind electricity generation in the UK grow rapidly over the 2010s. Offshore wind expansion starts later than onshore wind, but catches up by 2020. The expansion of solar PV generation slows and stops towards 2020, due to large cuts to support policies and network constraints.

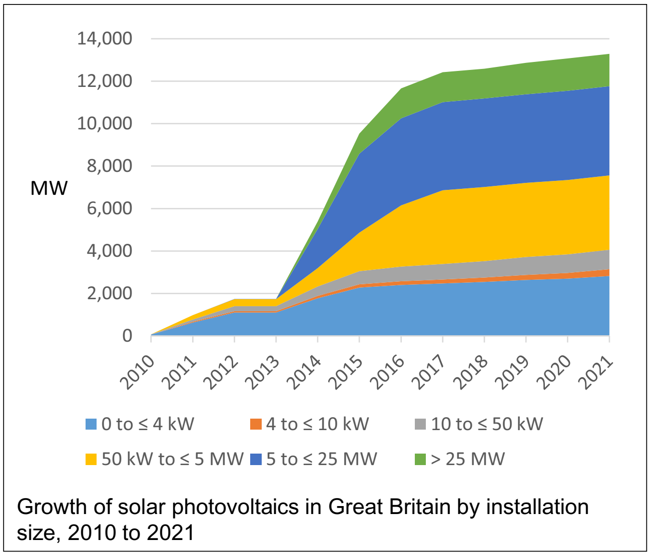


Fig. 2. Growth of solar PVs in Great Britain by installation size, 2010 to 2021. Residential rooftop solar (0 to ≤4 kW) makes up a small proportion of the rapid expansion from 2013 onwards.

Spending on R&D in the electricity sector, and especially in grids, collapsed after privatization at the end of the 1980s (34). While Ofgem had set up specialist working groups from the end of the 1990s to look at barriers to distributed generation, these did not have much purchase on decision-making (12, 33), in part because of the weakness of the distributed generator lobby. R&D was revived only in the early 2000s when Ofgem's chief engineer proposed a specific new funding mechanism (26). In 2010 this was extended and scaled up in a Low-Carbon Network Fund (LCNF) which supported more real-world trials, such as DSR with household consumers. Ofgem and the government also established a Smart Grid Forum to bring together grid companies and specialist ICT providers and to build a common vision (35).

However, the creation of a new niche for smart distribution grid R&D, while necessary, was not sufficient to ensure breakthrough into the regime. Under the LCNF, most progress had been made in technologies for monitoring power flows and equipment faults, but there were far fewer developments in new ways of operating grids (36). Most importantly, there were few signs that grid companies expected to use many of the technologies and practices coming out of R&D programs in their business plans to facilitate the expansion of low-carbon technologies (37).

By the end of the 2000s, civil society actors were offering visions of a transformed grid (38), and putting pressure on grid companies, the regulator and the government to make these visions real. The government made a number of changes over the decade to the regulator's duties to focus attention on decarbonization of the grid (26). In response to these pressures, Ofgem launched a review of its regulatory model, which resulted in a new framework explicitly adopting the aim of stimulating innovation (39). However, within the institutional arrangements of the electricity regime, Ofgem still had a high degree of autonomy (26), and with the organization's core capabilities in regulatory, rather than innovation, economics, this new framework retained the same basic structure that rewarded efficiency and penalized risk taking (33, 40).

This inertia in regime rules meant that networks often remained a constraint on wider system change. In the early 2010s, it became apparent that rapid growth of investment in solar PV far exceeded the conservative expectations of the distribution grid companies (33), and networks were becoming congested. The response of network companies was to offer solar PV developers interruptible contracts, meaning that the export of power from solar farms could be reduced or stopped in real time using ICTs if networks become congested locally (37). This approach solved the immediate problem but meant that renewable generation was frequently constrained off the grid, underutilizing low-carbon resources. It has taken almost a decade for distribution companies to start managing congestion in a more sophisticated way, through contracting for flexibility services from wider DER on a serious scale.[†]

Even here, the role of new technologies is very recent, with battery services being used by distribution grid companies for the first time only in 2020 (41). Instead, the main use of grid-scale batteries to date has been by the system operator in balancing and fine-tuning demand and supply (41). Drops in cost, new market opportunities, and clarification of regulatory status, has led to a large surge in planned investment in commercial-scale batteries (Fig. 3). However, as with solar PV, grid infrastructure itself has become a constraint on this rapid growth, with reports of waits of up to 10 y for grid connection for battery projects.

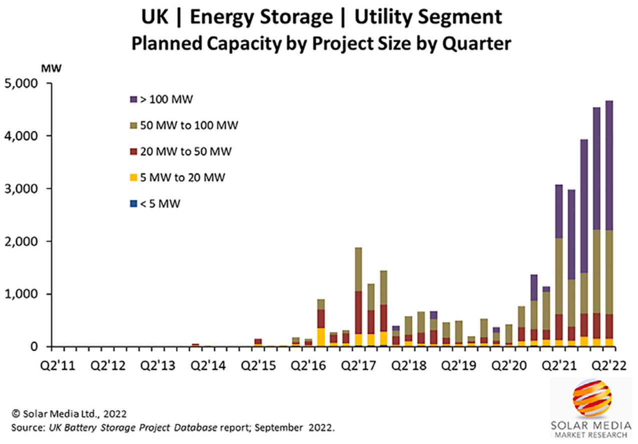
Previously niche technologies are now beginning to be adopted at scale by households. There are now over 850,000 rooftop solar PV installations in Britain, around 200,000 cars with chargeable batteries (42) and almost 100,000 heat pumps (43). This growth points to the possibility of a significant future potential DER, and while numbers are still small, some households are already involved in remotely controlled DSR via smart charging and even V2G services. However, the roll-out by utilities of the smart meters required for linking these technologies into the grid has been beset with technical problems (44) and is way behind schedule, with fewer than half of households with meters running in smart mode at the end of 2021.[‡] And as with grid-scale batteries, DSR and battery services from households are being aggregated and offered to the system operator for balancing, rather than to help manage congestion in grids (45).

Overall, the British electricity system has become more environmentally sustainable (46). Over the last three decades, renewables—especially solar and wind—have become a significant part of British electricity generation. Sources of low-carbon flexibility, increasingly important for even deeper adoption of intermittent renewables, are now also beginning to grow. However, this process has sometimes been slow and uneven, often because of the need to bring grid rules, regulations and practices into line.

By contrast, a deeper social transformation of the grid regime has been absent. Electricity generation has become more distributed in a technical sense, but not significantly in terms of ownership. While some niche technologies are now being incorporated into grid operation, incumbent regime actors retain key roles and determine which technologies are brought in, on what terms. Grid ownership remains largely protected by regulation, and large incumbent companies are major players in wind power. While ICT technologies comprise an increasing proportion of infrastructure, ICT supply firms are not yet integrated into network planning (12). There are some new entrants in solar PV and batteries, but even these are commercial actors investing at utility scale.

[†] Flexibility services – Energy Networks Association (ENA).

[‡] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1059591/Q4_2021_Smart_Meters_Statistics_Report.pdf.



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Source: *UK Battery Storage Project Database* report; September 2022.

Fig. 3. UK planned battery energy storage capacity grows rapidly since the start of 2021. This growth is driven by projects in the >50 MW range, i.e., grid scale.

Niche actors or initiatives that represent genuinely radical innovation in the electricity system remain marginal. In 2014, community energy projects represented only 0.4% of the UK's renewable electricity capacity, and have not grown since (47) (48). There have been experiments with new business models in community energy, local electricity markets and peer-to-peer trading, but these, along with micro-grids, face multiple market and regulatory barriers, including high costs of entry and licensing requirements for participation in wholesale and retail markets (49) (48, 50). These barriers in part reflect the fact that regime rules have been designed for, and to some extent by, large corporate incumbents (23).

Thus while three of the "D"s, i.e., decarbonization, decentralization and digitization, have happened to some degree in Britain's electricity system and grid infrastructure, the fourth "D," i.e., democratization, has not. This situation contrasts with some US states, such as California and New York, where more supportive policy, and different ownership and regulatory arrangements, including making network operation contestable, have allowed a growth in such radical innovations (15, 51). It is also different from some European countries, where the ownership of grids has historically been smaller in scale, making community entry into grids easier (50).

A more active role for prosumers in the electricity system would require not only changing regulation and opening up ownership, but also creating greater representation of the interests of such actors in system governance (52)(53). But such reforms may be needed to realize the full potential of DER. This is because trust in the smart grid is not simply about the technologies in themselves, but also about trust in the actors that consumers will interact with through those technologies. Consumers tend to be more enthusiastic about interacting with more democratic market structures, such as local energy markets or peer-to-peer interactions, than with traditional energy utilities (54).

However, it is unlikely that radical change will happen soon. The current direction of the British electricity system suggests a future hybrid model that will include some large-scale generation such as offshore wind and nuclear sitting together with distributed generation, grid-scale battery storage and industrial and commercial DSR. The role of households as prosumers in this future system is currently unclear, other than a concern for smart charging of EVs. The dynamics of the British transition may mean this will continue to be the case unless regulation, ownership and policy are significantly changed.

Conclusion

The climate imperative requires that electricity systems become environmentally sustainable, and at the same time, innovations in electricity technologies have opened up the possibility of more socially sustainable, democratic and inclusive systems. However, in practice transformations in electricity are often slow, uneven and ultimately limited, and transitions approaches can help illuminate the reasons for this. These approaches focus on how technical change within transitions interacts with social and political factors, especially institutional arrangements and rules in the existing regime.

Despite high-level commitment to climate goals, grid transformation in Britain has had particular challenges due to institutionally weak links to the electricity infrastructure sub-regime, a lack of electricity-specific targets, policy instability and the relative autonomy of a regulator working with strong logics of short-term efficiency and security. The British electricity system is changing, with more renewable energy, and the beginnings of a growth of potential distributed energy resources in the form of batteries (including in EVs) and demand-side flexibility. However, grid regulation, rules and practices have often been a constraint on the pace of change.

In addition, there are limits to social transformation in the British case that can also be understood within a transition framework. These limits are principally due to the difficulties faced by niche actors in challenging the grid sub-regime from outside. The virtual absence of local grid governance and new business models such as peer-to-peer trading and local markets, is due in part to the grid ownership model, with large corporate actors. As monopolies, such actors face regulation, but they also enjoy protection from competition and challenge. Making the electricity system more democratic in nature, increasing its social sustainability, would require not only the removal of specific regulatory and policy barriers, but also the breaking up of large network companies, or at least the opening up the governance of network areas to local actors such as community groups or local authorities.

The wider implications for sustainability science of such an approach is that transformation of infrastructures that underlie production–consumption systems requires not just new technology and operating systems, but also major reforms to institutions, sometimes including ownership, changes in institutional logics, and good alignment between the governance of such infrastructures and the wider policy context. In cases like electricity infrastructure, change cannot easily come from niche actors outside the sub-regime, while there is often inertia within, so ultimately governments and perhaps civil society organizations will be the key change agents.

Materials and Methods

The analysis refers to figures using data compiled from various sources, as described below. In addition, it draws on reports and policy documents from industry bodies, the UK government and the energy regulator, as well as secondary literature. Data for the figures were compiled as follows: for Fig. 1, Department for Business, Energy and Industrial Strategy (UK), Digest of UK Energy Statistics various years (https://data.gov.uk/dataset/894d91a9-5d13-4220-b9a2-e124e6436304/digest-of-united-kingdom-energy-statistics); for Fig. 2, Department for Business, Energy and Industrial Strategy (UK), Solar PVs deployment (https://www.gov.uk/government/statistics/solar-photo-voltaics-deployment); for Fig. 3, M. McCorkindale, The numbers behind the record-breaking rise of the UK's battery storage market. Energy Storage News, March 17, 2022 (https://www.energy-storage.news/the-numbers-behind-the-record-breaking-rise-of-the-uk-battery-storage-market/). Reprinted with permission from SolarMedia Ltd. The underlying data come from the UK Government renewable energy planning database (https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract).

Data, Materials, and Software Availability. There are no data underlying this work.

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