Waves of disruption in clean energy transitions

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Waves of disruption in clean energy transitions: Sociotechnical dimensions of system disruption in Germany and the United Kingdom

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ABSTRACT

Academic and policy literatures are seeing a growing discussion about ‘clean energy disruption’. However, the term disruption often lacks definitional clarity. Departing from the concept of disruptive innovation and based on a review of firm-based management and socio-technical transitions literatures, we derive four dimensions of system disruption: technology, markets and business models, ownership and actors, and regulation. We apply these dimensions to analyse the status of disruption in two exemplary countries pursuing ambitious low-carbon energy transitions: Germany and the United Kingdom (UK). The views of a diverse range of actors are investigated regarding how disruption is unfolding and what is seen as disruptive in the energy sector. Our analysis draws on 28 expert interviews, supplemented with a review of empirical studies. We find that despite comparable shares of renewables in the two countries' electricity systems, the scale of disruption in Germany significantly exceeds that in the UK, covering all four rather than just two dimensions. We also find a greater awareness of and resistance to expected further waves of disruption in Germany, as compared to the UK. Finally, we discuss the implications of the notion of disruption for understanding and governing socio-technical transitions.

1. Introduction

Transitions advancing a low-carbon future are imperative to meet the demands of the Paris Agreement and stay below 1.5 °C of global temperature rise [1,2]. Efforts are increasingly centring around how low-carbon transitions can be accelerated [3,4]. Energy is a key sector for these transitions, as it accounts for around 40% of global CO_2emissions [5]. Given the urgency of the climate change challenge, incremental change towards low-carbon energy systems is too slow and, thus, a more radical ‘disruption’ of incumbent fossil fuel based energy systems is needed [6,7].

The notion of ‘clean energy disruption’ has become widespread, typically referring to the transformative potential of a range of technological solutions. These include decentralised renewable energy technologies, smart demand response, the electrification of mobility, and digitisation and automation, as well as their combinations [8]. Building on Christensen's notion of ‘disruptive innovation’ (1997), the literature has largely focused on novel technologies and business models rather than system-level changes. To advance low-carbon transitions rapidly, we argue that bridging the conceptualisations of system-level transitions and disruptive innovations can generate new insights into how energy transitions unfold, and what effects they have alongside CO_2 emission reductions. Alongside Wilson and Tyfield [9], we, thus, argue that focusing only on technologies and business models makes limited use of the concept of disruption for analysing energy transitions. Thus, we extend Christensen's understanding by drawing on the literature of socio-technical transitions [10–12]. In the context of transitions, *disruptive innovations* are novel value propositions in the market [13] that derive from niche technologies [11,12] and have disruptive potential in the system [14], resulting in significant improvements in environmental sustainability. We define *disruption in the system* as radical interference in one or more of the elements of a stabilised socio-technical system, causing pressure to alter the system more than incrementally towards improved sustainability.

The term ‘disruption’ has been used in high level policy discussions in Germany [15], the United Kingdom (UK) [16], and the European

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Union (EU) [17], but also in the popular press [18]. However, 'disruption' is somewhat of a 'buzzword' [19,20] and suffers from definitional challenges [19,21–24]. Regardless, the term is used to denote occurring or anticipated change in energy at the systemic level. It is, therefore, important to understand in what ways disruption in different contexts is perceived to occur. In this article, we focus on systemic understandings of 'disruption' rather than discrete 'disruptive innovations'.

Based on previous literature, we create a framework for analysing different dimensions of disruption in socio-technical systems. We then analyse what kind of disruption (if any) has occurred in the socio-technical energy systems of Germany and the UK, to highlight differences in the extent to which different forms of disruption are occurring in the ongoing energy transitions. Based on 28 interviews with key stakeholders, we explore how actors perceive the changes taking place in the energy sector, and whether they regard such changes as disruptive. We also use already published material on energy transitions in these countries to understand the nature of systemic disruption. We offer a descriptive account on the nature of disruption in each country to move beyond 'uniform' and often normatively-loaded accounts of disruption [25]. Such an analysis can help to identify points of disruption, for policymakers and others, to design strategies how to alleviate tensions, avoid the negative effects of disruptive transitions (e.g. unemployment or social exclusion) and advance "just transitions" (cf. [26] by targeted strategies addressing different dimensions.

In Section 2, we derive our analytical framework combining ideas from firm-based management and socio-technical transition literatures. This is followed by our research case (Section 3) and the methodological approach (Section 4). Findings are presented in Section 5 and discussed in Section 6. We close by drawing policy implications for governing low-carbon transitions faced with potentially disruptive changes.

2. Disruption in socio-technical transitions: towards a systemic understanding

2.1. Disruption and energy transitions

In the context of rapidly diffusing renewable energy technologies there is a growing discussion on the need for 'disruption' in the global energy sector [18,27]. Interest is burgeoning in the potential role of disruptive low-carbon innovations in driving socio-technical transitions [28].

Seba describes energy disruption in terms of how technologies such as solar, battery storage and electric vehicles will fundamentally alter the 'energy architecture' of our lives, moving away from a resource-based system to an information-based one. This new architecture is based on an increased role for the consumer in being able to produce energy, leading to the demise of the traditional energy utility [8]. We argue that this rapid deployment of low-carbon technologies can too easily be labelled as 'disruptive' without sufficient consideration for the different dimensions and geographical unevenness of 'disruption'.

Much discussion on clean energy disruption builds on the firm-based management literature on disruptive technologies and innovation [29–31]. It argues that leading firms have been slow to react to technological changes catering to new customer wants and expectations, and as a consequence their market share and existing revenue streams have been significantly disrupted [32]. In this discussion, a plethora of recent technological developments have been identified as disruptive from electric vehicles to electronic cigarettes [33,11,34–37]. However, the term has been criticised for lacking definitional clarity, being vague and unhelpful [19,38,21,20,24]. From the sustainability transitions perspective, important is the altered production characteristics (lower emissions) of disruptive innovation [28]. The service to the consumer may be the same (e.g. electricity, heat, shelter) or different (e.g. new mobility services instead of private cars), and the organisation centralised or decentralised. However, these characteristics may influence the acceptability or legitimacy of the innovation and, hence, the speed of diffusion.

Recently, it has been noted that disruption could also be considered at the energy system level using a socio-technical perspective [9]. Yet, while some work that is focussed on energy systems has built on Schumpeterian insights regarding the 'creative destructive' forces of innovation [39], most studies in this area seldom refer explicitly to 'disruption'. Amongst the exceptions, Rosenbloom [14] describes how disruption involves a power shift from incumbents to new entrants or actors from other socio-technical systems, a change that may concur with institutional or technological changes, such as phase-out subsidies and new technology rollout commitments. Dijk et al. [11] argues that disruptive market innovation connects to regime transition or diversification. Geels [12] identifies disruption in socio-technical systems in terms of (rapid) speed of change. Differing from that, Lindberg et al. [40] connect it to the magnitude of change: "the degree of disruption… is about whether there will be more or less profound changes in the basic architecture of the socio-technical system."

To understand better the factors thought to make low-carbon energy transitions disruptive in Germany and the UK, we build on a combination of the firm-based management literature with the socio-technical transitions literature to analyse disruption at the systemic level. First, we posit that certain key dimensions of disruption can be derived from an in-depth reading of the firm-based literature on disruptive innovation, including but also extending beyond the early work of Christensen [30,41,38,42,11,43–46]. Second, the meaning of these dimensions can be interpreted in a more system-oriented way, through insights from the transitions literature [47]. Such an interdisciplinary interpretation of the dimensions of system disruption may offer a useful means of comparing and contrasting the disruptive qualities of socio-technical transitions, taking place in different sectoral and geographical contexts, to gain a better understanding of the consequences of different transition pathways in terms of which industries and actors benefit from disruptive processes and which are hindered by these changes. Connecting processes of disruption to systemic change chimes with broader work that seeks to connect meso-level activities around sustainability to system-level developments, noting that there is usually a disconnection between these different levels of analysis [48–51]

Given that the term disruption is increasingly used, more empirically nuanced understandings are necessary to illuminate how particular processes of low-carbon energy transitions may be more or less disruptive. Not least, associated questions are of some importance in the design of effective and adaptive policy [52]. Considerations regarding 'just' energy transitions [26] require paying attention not only to the environmental effects but also to how transitions can advance energy democracy or socially just changes. The dimensions of disruption that we outline below offer a streamlined way of identifying key empirical differences between socio-technical transitions towards low-carbon futures in different settings.

2.2. Towards an analytical framework for assessing dimensions and status of system disruption

Drawing from the firm-based management and the socio-technical transitions literatures we created an analytical framework that identifies four dimensions at which a socio-technical system may be disrupted: (1) technology, (2) ownership and actors, (3) markets and business models, and (4) regulation (see Table 1). The dimensions are interrelated but, for analytical purposes, we foreground what we argue to be usefully distinguishable but sometimes also competing understandings of disruption. Together, they allow for assessing the status of system disruption in a more nuanced and empirical manner.

2.2.1. Dimension 1: technology

The first dimension of disruption is 'technology'. It addresses how

Table 1
Dimensions of disruption in transitions.

Dimension of disruption	Explanation
Technology	- Novel technology disrupting dominating technology and infrastructure by differentiated qualities - Requires initial shielding from mainstream selection pressures
Ownership and actors	- Emergence of new actors in production and supply - Changing ownership of assets (in terms of kind of actors), with implications on justice and democracy - Incumbent actors' reduced influence or fight back
Markets and business models	- New value propositions and ways to capture value - Reducing market share of incumbent companies - New entrants and new business models from incumbents (connected to the actor dimension)
Regulation	- Dis-alignments between disruptive innovation and existing regulation, calling for regulatory change - Regulatory interventions to intentionally disrupt non-sustainable systems

particular new technologies, or technological or engineering effects, can be considered disruptive to the existing dominating system. This relates to how the qualities of a technology operate in different ways compared to existing established technologies, and how their novel characteristics pose potential problems for existing technologies and associated systems [29]. A classic example is the physical difference between digital music enabling a speed, sharing, and transfer of music which 'hard copy' music could not deliver [36]. The transitions literature differentiates between niche and regime technologies. For the latter, technological development occurs along trajectories within established technological paradigms [53] or socio-technical regimes [54]. In contrast, the former need nurturing and shielding in protective spaces to be able to develop [55,56] and then to (perhaps) disrupt the dominant regime.

Energy-related examples of potentially disruptive technologies include wind, solar, tidal and wave power, and associated micro-grids and storage solutions. These (niche) technologies fit with a decentralised energy system with intermittent renewable technologies, where energy might be produced closer to consumption and becomes more responsive to variable patterns of supply and demand [57]. This contrasts with the established centralised energy system with large, geographically remote and constantly running plants. Alongside possible beneficial effects like the strengthening of power quality or the flattening of peak demand, disruptive effects from a technological perspective may manifest in various ways, including how intermittent generation can also amplify spikes and troughs in the matching of supply and demand. Additionally, the physical infrastructure of the electricity grid may require significant transformation to accommodate and integrate these new technologies as part of 'grid modernisation' [58].

2.2.2. Dimension 2: ownership and actors

The second dimension of disruption, 'ownership and actors', covers two interrelated aspects: (a) changes in who owns assets; and (b) the emergence of new kinds of actors in energy provision and services. Early contributions on disruption identified that, because incumbents were focussed on optimising their existing products and catering to existing consumers, they would be unwilling to invest in new disruptive technologies and, as a consequence, new actors would be likely to appear [32,44]. The transitions literature highlights a range of 'distributed' actors beyond firms, and focuses on their different 'strategies and resources', and how ownership models in niches may come to challenge incumbent forms of ownership [59].

Indeed, new forms of ownership have emerged around renewable energy, contrasting the traditional utility model, including energy cooperatives and community energy [60,61], linking to issues of energy democracy and justice [62,63]. In addition, start-up companies may increase their influence over incumbent utilities [8]. Incumbents can also actively fight back, aiming to reduce competition from new players and expand their portfolio to renewable energy technologies [64,65].

Understanding ownership structures and the role of actors in energy transitions can unfold the politics behind processes of energy disruption. For example, Baker and Phillips [66] found that reconfigurations of national electricity sectors as a consequence of disruptive technologies are facing significant political and economic challenges rooted in countries' socio-economic context, such as ownership models and distribution inequalities, with important implications for the directionality and long-term success of energy transition. Unfolding the actors' constellations and the ownership models characterizing energy systems and their disruption provides significant insights into how institutional settings can effectively respond to social and technological drivers for low-carbon energy transitions.

2.2.3. Dimension 3: markets and business models

The third dimension of disruption is 'markets and business models', recognising that a change in the dominant business models can have a radical effect on the market shares of incumbent companies [31]. Business models are understood as stemming from 'value propositions' and the design of a "product or service that helps customers get a job done more effectively, conveniently, and affordably" ([60]: 1331). The transitions literature recognises that business models tend to become aligned as technological regimes stabilise, and differing firms conform to similar or complementary business models [67]. This alignment process makes it challenging for niche business models that capture value in different or incompatible ways to expand beyond the niche [49].

Changes in business models can have disruptive effects on the energy market, where new approaches to 'capture value' (e.g., through creating more demand-responsive tariffs that fit within the fluctuating energy prices) are created in connection to intermittent renewables [68,11,69]. The increasing deployment of renewables has been argued to pose a 'threat' to existing companies' business models, because new business models that provide a range of services (rather than the traditional energy commodity) will become increasingly important [70]. The transitions literature addresses also the broader role of market structure, the design of incentives and pricing – and how these factors may, in turn, influence changes in the business models of individual firms or utilities [11,71].

2.2.4. Dimension 4: regulation

'Regulation' is the fourth dimension we consider. Regulatory frameworks may not be able to keep pace with disruptive innovation [72] and are challenged as a result [73]. Regulation may also constitute a barrier to experimental solutions advancing low-carbon transitions [74]. Disruptive innovation may raise significant public policy concerns, creating demands for new forms of regulation [75]. For example, new 'platform' industries, such as Uber and AirBnB, have challenged existing regulatory frameworks designed for public transport and the hotel trade as well as employment [76], resulting in changing regulations in these areas. The transitions literature argues that, if niches are nurtured and supported adequately, they can diffuse and potentially destabilise existing regulations and governance arrangements around incumbent actors [77]. Regulatory changes may also be used to pave way for disruption at the system level [39]. For example, in the construction industry, regulatory intervention via changed building performance standards can seek to shape firms' technological and product competences and established practices in a disruptive manner [78].

In the energy sector, regulators in charge of managing transmission and distribution networks face significant challenges because of decentralised and intermittent renewable energy. These include dispatching responsibilities and a greater diversity of actors producing electricity rather than monopolistic vertically integrated utilities which established regulatory frameworks were based on [79,80]. Further, the digitisation of energy systems creates new challenges that are likely to require a massive regulatory overhaul.

3. Empirical case

Germany and the UK are large European countries (populations of 82.7 million and 65.6 million respectively) with ambitious long-term greenhouse gas reduction targets for 2050, with Germany aiming for a reduction by 80–95% [81] and the UK by 80% [82], compared to 1990. However, the pursued instrument mixes and the countries' decarbonisation pathways differ significantly [83].

3.1. Germany

Germany is known for its "Energiewende" and its share of overall renewable energy in electricity generation has increased from 5% in 1990 to 31% in 2015 [84,85]. Onshore wind, bioenergy, waste energy, and solar PV have been the dominant renewable energy technologies (Figs. 1 and 2). Despite CO_2 emission reductions, Germany's continued reliance on domestically mined lignite presents a notable climate change challenge [86]. The decarbonisation of heat also faces considerable challenges [87] and the decarbonisation of transport is significantly lagging behind electricity and heat [88]. Germany remains the largest contributor of GHG emissions in Europe, and without the implementation of additional climate policies will miss its 40% CO_2 emissions reduction target for 2020 [89].

To understand Germany's unique decarbonisation pathway it is imperative to remember the country's long-standing public opposition movement towards nuclear power. Politically, this bottom up movement has manifested itself in a strong presence of the Green Party [90,91] which was fundamental to the adoption of the 'Nuclear Exit Law' in 2000. While nuclear phase-out was reconsidered by Merkel's government in 2010, after the Fukushima nuclear accident in 2011, Merkel implemented the nuclear phase-out by 2022 with cross-party support [92], giving the expansion of renewable energies additional momentum [93].

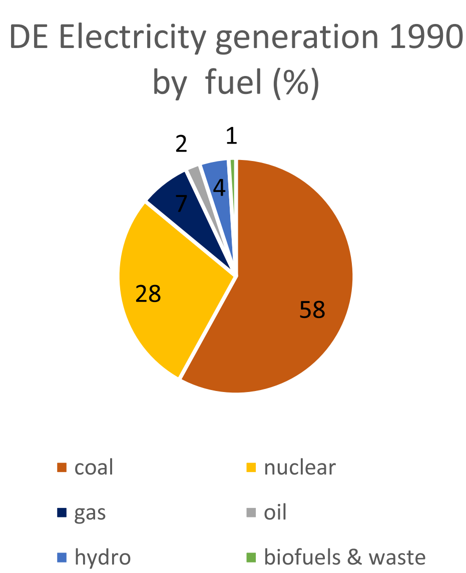

Fig. 1. German electricity production 1990 (%).
Source: IEA [100].

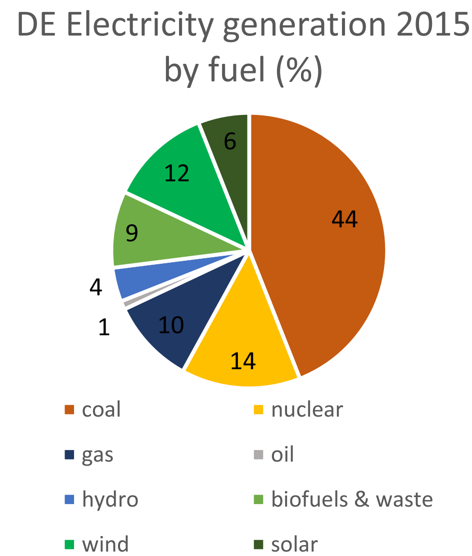

Fig. 2. German electricity production 2015 (%).

The growth of Germany's renewable energy portfolio is largely a result of long-term policy commitments. In the 1990s, a number of instruments were set to encourage the expansion of renewable energy [94], including the '10,000 roofs programme' updated to '100,000 roofs programme' to promote the deployment of solar power [95,96]. In 2000, the 'Red-Green' coalition government adopted the Renewable Energy Sources Act (EEG) which has become the core policy for accelerating the energy transition [97]. The EEG introduced technology-specific feed-in-tariffs guaranteed for a period of 20 years and priority access to the grid. It has been regularly amended to reflect socio-technical developments (e.g. drop in PV prices) and changing socio-political priorities (e.g. switch to auctions and introduction of expansion corridors) [98,99].

3.2. United Kingdom

In the UK, the share of renewable energy in electricity generation has increased from around 1% in 1990 to nearly 27% in 2015 [100] Most of this growth has materialised in offshore wind and bioenergy (Figs. 3 and 4). In addition, much coal generation was replaced by gas within the 'dash for gas' in the 1990s [101], leading to significant emissions reductions. Similar to Germany, the decarbonisation of heat and transport face considerable challenges and shares of renewable energy in these sectors have remained low [102]. There are concerns that the UK is not on track to meet its fourth carbon budget commitments of reducing emissions by 51% by 2025 albeit significant advances made in decarbonising power supply [103].

Changes in the electricity generation mix have resulted from a variety of factors [101]. Notably, the UK set the world's first legally binding climate change mitigation plan, the Climate Change Act in 2008 [104]. Renewable energy has been supported during the last three decades through various policies, including the Non-Fossil Fuel Obligation (1991), the Renewables Obligation (2002), Feed-in-Tariffs (2008), and Contracts for Difference (2013). The UK also introduced a Carbon Floor Price in 2013 [105] which somewhat compensates the weak price signals from the EU Emissions Trading System. In 2017, the country committed to phase out unabated coal generation by 2025, being amongst the first to make such a commitment [106,107].

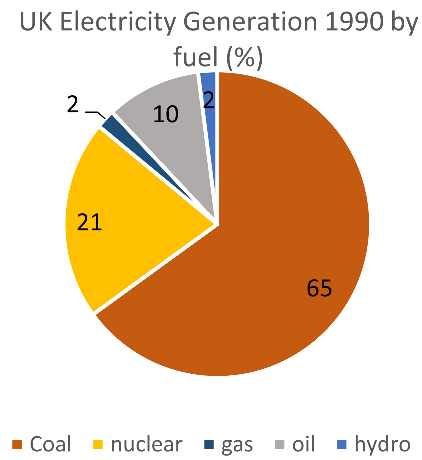

Fig. 3. UK electricity production 1990 (%).
Source: IEA [100].

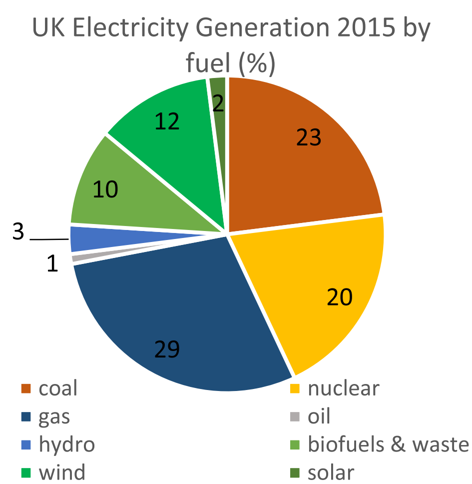

Fig. 4. UK electricity production 2015 (%).

Simultaneously, contrary energy policy developments prevail: the UK is the only country in Europe that actively pursues and invests in hydraulic ‘fracking’ of natural gas, and it has the most ambitious nuclear new build agenda of the developed world [108] while the global nuclear industry is in decline [109].

4. Empirical research method

In our empirical investigation of disruption, we used in-depth interviews as the primary data source. Selecting interviewees from a variety of backgrounds, interviews were used as systemic evidence [110] to analyse energy disruption. Expert interviews were conducted during November 2016–March 2017 by the first and second author, comprising 15 interviews in Germany and 13 in the UK. Interviewees were selected to represent different types of actor groups with significant expertise on the energy sector (Table 2).

The data collection was based on a semi-structured interview guide, with questions on the interviewees’ views of what disruptive changes (if any) had occurred in the country's energy system and prospects for upcoming disruptions. Open-ended questions were followed up by prompts arising from the analytical framework pertaining to the four dimensions of disruption. All interviews were recorded, transcribed verbatim and the German ones translated into English.

For the data analysis, the authors jointly developed an initial coding framework based on the analytical framework. This initial coding framework was then refined on the basis of test coding. The aim of the test

Table 2
Interviewee categories and number of interviewees per country.

Interview category	Germany	United Kingdom
Research	3 (DE1, DE3, DE7)	1 (UK1)
Industry Association	4 (DE8, DE9, DE10, DE14)	4 (UK3, UK5, UK12 UK13)
Trade Union	1 (DE15)	1 (UK7)
Ministry/ Politician	3 (DE2, DE12, DE13)	4 (UK2, UK4, UK10, UK11)
Utility	1 (DE4)	1 (UK8)
Think tank/ NGO	1 (DE5)	2 (UK6, UK9)
Total number of interviews	**15**	**13**
Total duration of interviews	19.8 h	13.6 h

coding process was “that a single knowledgeable coder may be reasonably confident that his or her coding would be reproducible by other equally knowledgeable coders”, i.e. *intercoder reliability*, and reconciling discrepancies in coding by achieving *intercoder agreement* ([111]: 297). Test coding was carried out by five authors coding one interview individually, followed by a joint discussion to compare coding, revise the coding framework, and agree on a uniform interpretation of codes. To enhance the reliability of our analysis we conducted two further rounds of comparative coding until a satisfactory coherence in the interpretation of the codes and the coding procedure was achieved and a final list of codes was agreed upon. Based on this, subsequently, the first author coded all interviews in NVivo.

To obtain an initial impression of the data, we ranked the codes according to their frequency of occurrence. The first author then created an Excel sheet containing all codes pertaining to the analytical framework in which, for each interviewee, he summarised their perception of the status of disruption for the four dimensions in the framework. This assessment was discussed with the second and third authors, considering alternative explanations and going back to the original interviews when needed. The assessment was then fine-tuned accordingly, based on which for each code the first author derived the overall findings across all interviewees. This was again scrutinised by the second and third author in joint discussions on the overall interpretation of the findings. Based on these, the first author then consolidated the Excel table, which served as basis for writing up our findings.

Rather than taking the responses of interviewees purely at face value, we triangulated the interview findings by scrutinising them with secondary data. For this, the first author conducted a literature review based around the key words of “disruption”, “disruptive innovation” and “energy transition” combined with “Germany” and “UK” in Science Direct, Scopus, and Google Scholar. For each country, this resulted in a list of over 30 peer-reviewed articles, reports, and policy documents focussed on disruption in the context of energy transitions. This empirical literature provided important contextual information regarding each case study country, which allowed triangulation of emerging interview findings in terms of the dimensions of disruption under question.

5. Findings on dimensions of disruption in the German and UK energy transitions

5.1. Disruption in Germany

For the electricity sector, a majority of the German interviewees (12 of 15) differentiated between a ‘first wave’ of disruption that has already happened (hitherto referred to as the *first electricity disruption)* and an impending ‘next wave’ of disruption (*second electricity disruption)*. In addition, five interviewees also outlined a disruption set to take place in other associated sectors (*cross-sectoral disruption*). In the following section, we present the extent of perceived disruption for all four dimensions and how these were discussed in relation to the three waves of disruption in Germany.

5.1.1. Dimension 1: technology

5.1.1.1. First electricity disruption. Changes in electricity supply through the increasing penetration of renewable energy sources (mainly onshore wind and solar) was identified by all 15 respondents. The decentralisation of energy technologies was mentioned as an important feature of disruption, with repercussions on the grid infrastructure (7 interviewees). One interviewee highlighted that disruption had been generated only by decentralised low carbon technologies: *"not large-scale renewables – that is offshore wind or larger biomass plants – but rather…decentralised plants"* (DE3, Research). The German electricity system was previously based around large power plants feeding electricity directly into the transmission grid, but with increasing decentralised generation, *"the distribution network has become increasingly important."* (DE9, Industry Association).

5.1.1.2. Second electricity disruption. Seven interviewees viewed that storage technologies are pivotal to the second wave of disruption. The reason behind this is the intermittent nature of renewables which represents a key technical challenge for which solutions, such as storage and load shifting, are required to enable the further expansion of renewables [112]. The second wave would in part be driven by technological change revolving around storage, where *"the key drivers are coming rather from the spheres of technology…when storage batteries are cheaper than PV modules, then it'll go by itself"* (DE4, Utility). Regarding further decentralisation of electricity, missing storage solutions were identified as a potential barrier: *"…the necessary infrastructure is lacking for handling the rising volume of renewables. This includes storage"* (DE2, Ministry).

Digitisation was identified as an important part of the second wave (five interviewees). Views were, however, contradictory regarding its importance. One interviewee saw that *"the whole field of digitisation is really setting out right now…"* (DE13, Ministry) and another pointed out that *"something that might be disruptive…with regard to the future, is the issue of digitisation"* (DE8, Industry Association). It was also stressed that the possibilities enabled by digitisation could be hyped, and that digitisation as such was not driving disruption: *"Digitisation is a tool… It's like Uber without cars or Airbnb without apartments. It's first of all necessary to roll out the hardware"* (DE4, Utility).

5.1.1.3. Cross-sectoral disruption. The potential coupling of electricity and mobility systems received attention from eight interviewees. Electro-mobility was one of the main technological developments mentioned (five interviewees), with the disruption yet to occur. *"Electro-mobility is certainly – also because of the great importance of the automobile industry in Germany – the next disruptive case"* (DE12, Ministry). In this context, the importance of batteries or hydrogen was highlighted. However, four interviewees indicated that progress on electro-mobility had been slow: *"in Germany the transformation to electro-mobility is lagging strongly behind other countries…because simply the car companies are so powerful that they prevent legislation"* (DE7, Research); illustrating the interdependencies between technology, actors, markets and regulation. These four interviewees highlighted that resistance by incumbents to further waves of disruption through electric vehicle rollout is significant, with the dominance of the German automotive sector being a key reason for this.

The disruption of sectors, such as mobility combined with the second electricity disruption through digitisation and storage, would lead to divisions between different sectors dissolving with new cross-sectoral applications of innovations. An interviewee stated that *"at the moment there are many, many parallel developments…if that [electric vehicles] really diffuses, then it will have an unbelievably great impact on the energy system, and that doesn't even have to do anything with energy, but with mobility"* (DE3, Think Tank). This issue of 'sector coupling' was discussed by five interviewees, and was seen not only in relation to electrifying mobility but also heat. As one interviewee stated regarding household generation: *"many, many people have now started…to install PV roof units and similar things everywhere. They are saying, if I can generate up to 70 per cent of my own electricity demand with a relatively affordable storage unit, and can also significantly support my heating needs with it [PV], then I'll do it."* (DE9, Industry Association).

5.1.2. Dimension 2: ownership and actors

5.1.2.1. First electricity disruption. The first electricity disruption was primarily driven by new actors (9 interviewees), including start-up companies, individual households (particularly through the development of PV), farmers, and energy cooperatives that now have a significant stake in the energy system. The energy system was 'challenged' *"…in the regard that it suddenly became possible that a variety of decentralised actors play a role"* (DE15, Trade Union). Ownership structures were a crucial consideration, with the energy cooperative movement being a main driver of the initial wave of disruption (identified by five interviewees). The role of citizen-led energy cooperatives and community energy groups in changing the ownership structure of German electricity generation is well documented [60,113,91,114,115]. In Germany there are over 1000 energy cooperatives [116] and around 51% of Germany's renewable capacity is owned by citizens and farmers [117,114].

5.1.2.2. Second electricity disruption. A key theme that emerged in the interviews was that those actors that have traditionally owned electricity production capacity (utilities) may not own it in the future. The increased role of the consumer and households as key actors could further erode the revenue base of conventional utilities (seven interviewees). In the second wave, there would be more actors involved in driving energy policy: *"I see that investments will be taken much more by new actors, also, by very heterogeneous actors, by people, by individual households."* (DE11, Research). With the move towards the provision of energy services tailored to the needs of these 'prosumers', and changes such as digitisation and the importance of information in general, four interviewees highlighted that new actors may enter the energy scene from the IT and services sector: "*the other key word…is: platform economy, that is the Googles, Facebooks of this world, who penetrate areas that have formerly been the domains of the public utilities, with the marketing structure that they have, because they…have a close relation to the customers"* (DE13, Ministry).

The direction of the second wave of disruption is, however, uncertain. Four interviewees saw a role for incumbent companies particularly in relation to technologies like offshore wind: *"there will probably also be centralisation again, not back to a small circle [the 'big four']… but to a somewhat smaller circle [of large utilities]. I mean, offshore, for example, these are of course really big infrastructure projects that only big energy suppliers can really manage"* (DE8, Industry Association). Commitments to a 'diversity' of actors still seems to be important in the German context: *"there was a task force 'Akteursvielfalt' [actor diversity] in the BMWi [Ministry of Economic Affairs], where they gathered many different actors over several months and looked at how the tendering system can be designed in a way that the broad participation can be maintained"* (DE14, Industry Association). These discussions relate to the policy change from feed-in-tariffs to tendering in the EEG but more broadly also to ongoing developments and debates regarding the German Energiewende where future scenarios could be more centralised or decentralised, depending on key policy decisions and socio-technical developments in the next few years [118].

5.1.2.3. Cross-sectoral disruption. Four interviewees highlighted disruptive changes to ownership and actors that were potentially on the horizon for the German automotive industry, due to changes particularly related to competition from abroad that could disrupt German companies' lead role: *"There clearly will be disruption in the car* *manufacturing industry…I am afraid that Germany might suffer on this disruptive transformation of the mobility sector"* (DE7, Research). Similar to how German utilities were caught off guard or reacted too slowly to the rise of renewable energy, the same trend may occur in relation to car manufacturing: *"you get a bit afraid that a similar thing will happen with the automotive industry, and that a similar thing will happen with the chemical industry"* (DE5, Think tank). This relates to new actors emerging on the scene in other countries that are said to be dominant both in terms of production and market share. For example, China is producing 43% of the world's electric vehicles compared to Germany at 23% [119], and companies such as Tesla from the USA are important competitors in electric vehicles. Finally, the increased role of the consumer was related to new business models to facilitate cross-sectoral solutions at the household level through the integration of electricity, heat and transport (5 interviewees).

5.1.3. Dimension 3: market and business models

5.1.3.1. First electricity disruption. The disruption of existing business models of incumbent companies through the merit order effect[1] has already been established in the literature [70,121] and was confirmed by eight interviewees. With specific reference to big utilities like RWE and E.ON, a civil servant described the consequences for utilities of *"volumes of renewable electricity that had flooded the system"* whereby "*traditional power stations encountered problems and had to be shut down, the power exchange price fell and utility companies' business models were suddenly called into question"* (DE2, Ministry). Consequently, traditional utilities have split their organisational structure between conventional and renewable supply and are searching for new business models in order to survive. *"You see this in the splitting up of E.ON and RWE. They have now realised that those pushing the old business ideas are no longer advancing"* (DE 1, Research).

5.1.3.2. Second electricity disruption. Related to the technological developments, such as digitisation, automation and storage, comes the question of business models in which consumers play a stronger role, highlighted by seven interviewees. This *"new downstream development"* (DE3, Research) is building on decentralised variable generation and a greater role for consumers. Thereby, it requires incumbents to reformulate their business models for the 'second wave': "*There's a radical change on the horizon, and the major players are thinking about how to stay in business"* (DE2, Ministry). An interviewee from a utility company described this reorientation with *"close customer contact"* in which they need to be able to *"react very quickly to customers' desires" (*DE4, Utility). It was pointed out that a lack of growth in traditional markets would be a key driver for such a reorientation, including the search for new strategic partners: *"if we find that traditional markets aren't enjoying growth anymore …then we will have to consider whether to expand our portfolio to include this kind of business… or we can join forces with others…who already have the right customer contacts" (*DE4, Utility).

The interrelated nature of the dimensions of disruption is exemplified by the foreseen key role of the consumer influencing business models towards a focus on the provision of energy services, rather than the direct sale of electricity or devices: "*I think that the current business model is going to change [..] we think that in the future the money will be made rather by providing the right services than by selling devices"* (DE10, Industry Association). This also related to the rise of storage and digitisation enabling more efficient delivery of services, which may undercut traditional utilities further. An interviewee questioned whether *"the margins that many municipal utilities have today [can] be preserved in the medium term as supplier changes, tariff levels, and the purchase and supply of energy become increasingly automated and digitised, and the only things that matter are efficient processes and not much else"* (DE1, Research).

5.1.3.3. Cross-sectoral disruption. E-mobility is thought to impact on household energy services and to interlink with issues around storage: *"regarding flexibility, electro-mobility has also a certain role as energy storage and flexibility option in this context*" (DE12, Ministry). Emphasis was also placed on 'start-ups' offering a range of services across sectors: *"many start-ups doing all kinds of things, such as aggregation, metering, charging station ideas and storage facility construction, of which there is today much more due to sector coupling. This is a very big topic [..] mobility, heating, flexibility and digitisation*" (DE9, Industry Association). This quote shows the interrelated nature of differing dimensions of disruption as technological and business model factors align. So, disruptions in different sectors are likely to join up as cross-sectoral changes and new companies may focus on business models that integrate a range of services across sectors.

5.1.4. Dimension 4: regulation

5.1.4.1. First electricity disruption. In the context of the first electricity disruption, regulation was mentioned by six interviewees. The rapid deployment of renewables on the grid has disrupted the usual regulatory practice due to more tasks for regulatory agencies. In response, more dialogue is required between policy makers and regulatory bodies. One interviewee stated that due to the rapid growth of onshore wind and solar, there have been additional pressures placed on grid operators and the Federal Network Agency (Bundesnetzagentur, BNetzA), leading to changes. An interviewee from a Government Ministry noted that *"the role…[of the regulator]…has changed massively",* where more dialogue between policy makers and regulator is now required to manage the changes underway. Further, *"…due to the enormous changes in the energy system we are in a – often critical, in fact – dialogue: how far does this go? What are the political guidelines?"* (DE 13, Ministry).

These challenges have led to a number of regulatory changes. Amongst others, more cooperation mechanisms have been established between different grid operators, particularly around the increasing need for "re-dispatch" that has *"forced them to change how they work"* (DE 6, Research). As a consequence, information-sharing and communication have increased between grid operators, changing the usual regulatory arrangements: *"…there's more cooperation across grid operators to ensure that stability can be maintained at a reasonable cost"* (DE6, Research). That is, the German energy transition has created new demands from regulators, leading to *"…the addition of many, many tasks for the regulatory authority"* (DE10, Industry Association). For example, *"The Federal Network Agency was very active in raising certain efficiency potentials with network operators and improving certain processes. The market for balancing energy has become much more efficient"* (DE1, Research).

5.1.4.2. Second electricity disruption. Regulation was seen as a barrier for the second electricity disruption, because a new regulatory framework, tailored to a more flexible and decentralised electricity system, was missing (7 interviewees). *"I do think that the Energy Industry Act (EnWG) in its current state has to be reviewed… you'd have to ask yourself if all the regulations that were mainly made for a centralised system do still fit in the new system",* because *"drivers for the network expansion are less and less coming from the level of the transmission grid, but rather from the consumer side"* (DE10, Industry Association). Another interviewee outlined the problems of developing regulatory frameworks to integrate new electricity producers: *"…what does this actually mean for the integration into the electricity market from the perspectives of all these grid operators? …Is it the public utility that is active in the region and makes single contracts with – I don't know – 20,000 individual PV-plant operators? How is that supposed to work? So, this question: how do we integrate those into the electricity market in the future?"*

[1] The Merit-Order Effect refers to "the lowering of power prices at the electricity exchange due to an increased supply of renewable energies" [120].

(DE14, Industry Association).

In relation to storage, *"the regulatory framework conditions are simply missing"* (DE8, Industry Association). For digitisation, *"…the pace of the regulation can be seen as an obstacle"* (DE10, Industry Association). This broader regulatory challenge was also recognised by a civil servant: *"It [the regulatory framework] is still too rigid and still has too much of an old-world approach, a purely distributive network function, and too little function as a highway from below for decentralised generation and distribution and aggregation, storage and flexibility. There's still too little of this function in [*the *BNetzA]. It definitely has to do something. And the Network Agency knows this"* (DE13, Ministry).

5.1.4.3. Cross-sectoral disruption. Pressures on regulatory frameworks through increasing sectoral integration were a theme discussed by four interviewees. One interviewee highlighted that a careful approach to regulating changes was being taken: "*With sector coupling there are two completely new areas coming in – heat and transport… But where we are deliberately moving very, very carefully and considerately, to say: can we really find a good access point? Or are we making a mistake if we create certain situations that we won't be able to control later on?"* (DE13, Ministry). Another interviewee highlights current regulatory barriers linking to wind, where "*in terms of sector coupling…here we of course have to choose other systems. There we come up against regulatory barriers. If I want to use electricity for heating,* i.e. *power to heat, and have to pay a string of duties, then that's difficult."* (DE4, Utility). While data was more limited on this topic, initial signs show that the regulatory conditions require adaptation to facilitate further sectoral integration, which will, in turn, affect other dimensions of disruption, including business models.

5.2. Disruption in the UK

The majority of interviewees from the UK (7 of 13) felt there had been 'some' disruption in the UK electricity system, while a minority (3/13) felt there had been no significant disruption. Five interviewees underlined a key period where disruption was beginning to take place, during 2010–2015. However, following significant policy changes taking place in 2015 disruption was being curtailed. We unpack this perceived status of a contested disruption below.

5.2.1. Dimension 1: technology

While all thirteen interviewees noted the growth in low-carbon generation over the past ten years, five interviewees pointed out that this had largely been based around offshore wind, whereas decentralised renewables had only grown more rapidly since the UK established Feed-in-Tariffs in 2010. Consequently, eight interviewees perceived that technological disruption had not occurred despite the growth of renewables. One respondent put it simply: *"I don't think we have seen the disruption from genuinely decentralised renewables just yet"* (UK5, Think tank).

However, some disruptive challenges to the national grid caused by the growth of intermittent renewables was recognised by five interviewees. For example, one interviewee pointed out the 'voltage problem' where *"the changes that have been taking place over the last ten years have led to a change of characteristics such that now there are hours and hours and hours of the year when the voltage is going up and up heading – I think they got up to* 419 kV. *The operational limit is 420kV"* (UK10, Regulation). These concerns have also been raised in the 'System Operability Framework' documents produced by the National Grid, which highlight the technical challenges at the grid level posed by variable supply and more demand led policies [122].

Finally, four interviewees mentioned the roll-out of 'smart meters' which would see digital technology being used to facilitate a greater role of the consumer in the energy system and which has been a key focus of the UK government [123,124].

5.2.2. Dimension 2: ownership and actors

'Big players', i.e. incumbent energy suppliers, still dominated the energy system (5 interviewees). While the market share of incumbent utility companies, 'the big six', had reduced from around 100% in 2008 to 85% by 2015, the prevalence of new ownership models around renewable energy is notably low [125]. As noted by one interviewee, *"a large part of the industry is very monopolistic"* (UK10, Ministry) and has remained in place. This was contrasted with other European countries: *"in Germany […] if you look at the way their PV is distributed, it is across a huge number of organisations – your Bavarian farmers, this sort of stuff –whereas in the UK, it is much more utility-scale, big solar farms."* (UK3, Industry Association).

The small penetration of community energy schemes was also mentioned by four interviewees: *"Community and locally owned stuff has not become a significant part of the system in the way that it has in Germany, and that reflects the politics"* (UK5, Think Tank). In 2014, the UK ministry in charge of energy policy launched a national Community Energy Strategy, signifying "*remarkable recognition of grassroots initiatives in sustainable energy*", while it has still to a large degree remained a grassroots activity ([126]: 408) .

5.2.3. Dimension 3: market and business models

The interviews pointed to the electricity market in the UK still being dominated by the 'big six'. As stated by one interviewee *"electricity policy is essentially dominated by the perceived need to basically base our electricity system around a relatively small number of relatively large generating sets, which hasn't changed since the '50s"* (UK9, Think tank). New market players struggle to gain hold unlike in countries, such as Germany, where incumbent business models have been put under substantial pressure by new players [127,128]. One interviewee noted that the lack of a 'flexibility' market[2] in the UK was an issue preventing innovation in business models around energy provision: *"We don't have competition in the wholesale market. That's a major barrier…and on top of that we've layered all these auxiliary services, and a capacity market outside an already imperfect market structure. It is a very bad picture from an innovation point of view"* (UK8, Utility).

Five interviewees pointed out that further disruption of business models may be on the horizon with new policies supporting increased roles for consumers. In relation to the rollout of 'Smart Meters' one interviewee noted that *"the more that we get the concept of Smart Meters and beyond Smart Meters, where there's going to be interaction between consumer and system… that's where I think the innovation [in business models] will happen"* (UK4, Ministry). Similarly, recent overarching policy developments have, rhetorically at least, committed to unleashing new business models that enhance the role of the consumer and to supporting new actors through R&D and other resources rather than just incumbents [130].

5.2.4. Dimension 4: regulation

The potential disruption of the regulatory frameworks designed by the Office of Gas and Electricity Markets (OFGEM) in which the grid operator, the National Grid, carries out its functions, was discussed by five interviewees. Grid regulation is increasingly being put under pressure by decentralised and household forms of energy production like solar, efficiency and electric vehicles: a *"new governance framework"* is needed because *"…for example…electric vehicle manufacturers coming along with really neat apps so that you can charge your car at the best price*

[2] A power system with an increasing share of intermittent renewable generation entails certain risks and uncertainties. This requires policy makers to incentivise flexibility and the ability to adapt to changes in levels of power production and demand. This includes financial incentives for utilising energy at certain times in the day to match supply and demand, and developing business models based around solutions including thermostat-based demand response, aggregators, and small storage providers [129].

or the lowest carbon or whatever you want. Potentially, those parties could shut down the National Grid" (UK10, Ministry). An interviewee saw that there was not a 'system architect' in place that could oversee this activity, because the National Grid oversees the transmission network, whereas distribution networks play a largely passive role (UK10, Ministry).

Another interviewee pointed out that, with the growth of renewables and climate change concerns, regulation had substantially changed to a direction, where government played more of a role in directing regulatory frameworks: *"The way we regulate and govern the electricity sector, compared with, say, 1998 when full competition was finally introduced, is unrecognisable"* (UK1, Research). However, the period of potentially disruptive regulation for decentralised renewable energy technologies (2010–2015) was rather short-lived, limiting the extent of disruption in markets and business models. Yet, in the context of smart meters one interviewee pointed out that *"in the context of trying to get many of those actors to invest on low-carbon technology, the whole smart metre rollout… Government now needs to intervene to get anything to happen"* (UK1, Research). It seems then the government is less willing to intervene in the regulatory process to favour renewables than before.

6. Discussion

Both Germany and the UK are attempting ambitious energy transitions in which renewable energy technologies play a leading role [83]. Our empirical analysis sheds light on the extent to which the associated system changes are understood to be disruptive and how disruption may be portrayed differently in the two countries (for a summary, see Table 3). We argue such a focus on disruption is important to identify the effects of energy transitions beyond CO_2 emissions, i.e. for policy makers to recognise also non-technological elements of transitions, and explicitly address questions around just transitions and energy democracy [26,62].

More broadly, this article emphasises the value of connecting a meso-level focus on disruption with more macro-level systemic developments. This connection enables a better understanding of how particular business model or ownership disruptions can influence broader systemic change but also how particular types of disruption are influenced by wider system developments, which has been recognised as an important area for further development for sustainability research more generally [48,67,49–51].

When thinking about the broader governance implications of disruption in Germany and the UK, two interrelated issues stand out – *ownership and actors* and *regulation*– and how these may influence the *rate, direction* and *acceptance* of disruption. Ownership and the emergence of new actors was identified as the key difference between the two countries. New actors have driven the first electricity disruption in Germany, while new actors have not had a significant impact on the UK energy transition. The role of actors is crucial in the overall disruption pertaining to (a) how new business models and markets unfold, and (b) the degree to which regulation is flexible to allow technological and business model disruption, and is disruptive in itself in destabilising existing non-sustainable infrastructures, markets and business models [39]. While incumbent power producers may have more resources to advance transitions, we find that disruption in ownership and actor configurations is more likely to support changed beliefs and practices. This is supported by Kelsey and Meckling [131], who showed that independent power producers dominate the renewable electricity sector in Europe and the United States, influenced by market effects of technology disruption. Decentralised energy transitions have been argued to reshape political power structures [132].

Our findings, however, show the dominance of incumbent power producers in the UK energy transition. In Germany, the emergence of new energy system actors and commitments to ideas of actor diversity contrasts with the narrower range of actors integrated in decision-making and regulatory processes in the UK. In particular, the rise of the

Table 3
Summary table of German and UK energy system disruption in 2017.

Disruption	Germany	UK
Dimensions		
Technology	• Decentralisation of energy supply through solar and onshore wind, plus grid challenges *(1st electricity disruption)* • Disruption through digitisation and storage anticipated *(2nd electricity disruption)* • Disruption through electric vehicles and power to heat anticipated *(cross-sectoral disruption (3rd))*	• Substantial growth of wind power, mainly large-scale offshore wind • Grid challenges caused by intermittent supply including voltage issues • Some see smart meters as a precondition of a 'second wave' disruption *(potential 2nd electricity disruption)*
Ownership & actors	• Broadening of ownership (e.g. cooperatives, farmers and citizens) in renewables *(1st electricity disruption)* • Increasing role of the consumer & various new actors from non-energy domains, including start-ups and IT sector *(2nd electricity disruption)* • Ownership of German companies in electro-mobility production potentially challenged by competitors (e.g. in China and USA) *(3rd cross-sectoral disruption)*	• Still dominated by 'big six' suppliers • Minimal role for community energy or consumers as yet, while government strategy for community energy exists
Markets & business models	• Disruption in business models of incumbent electricity suppliers leading to significant revenue loss *(1s electricity disruption t)* • Search for new service-based business models based on close consumer contact *(2nd & 3rd disruption)* • Potential importance of business models based around 'platform' economy *(2nd & 3rd disruption)*	• Despite renewables expansion still largely based around conventional business models by large incumbent suppliers • Consumers mainly staying in a passive role
Regulation	• Increased information-sharing and collaboration between network operators *(1st electricity disruption)* • Lack of adjusted regulatory frameworks acting as potential barrier to further disruption *(2nd electricity disruption)* • Regulation moving too slowly in relation to cross-sectoral developments *(3rd cross-sectoral disruption)*	• Electricity market reform and capacity market • Signs of disruption 2010–2015, later diminished • Regulatory barriers to more consumer involvement • Significant challenges faced by OFGEM in regulating the operation of National and distribution Grids
Status	• Three waves of disruption: ○ *first electricity disruption* has already occurred (with disruption on all four dimensions) ○ *second electricity disruption* and *cross-sectoral disruption* expected to take place, with potential regulatory and other barriers	• While experiencing technical challenges at the grid level and rapid growth in renewable energy, the UK has not undergone a significant disruption; business models and ownership models have not been radically changed; centralised supply paradigm remains in place. • Potential early moves to empower consumers and expected regulatory reforms *(2nd electricity disruption)*.

cooperative movement and prominent role of community energy in driving the energy transition in Germany is frequently highlighted; while in the UK, similar initiatives [126] have not yet disrupted the energy system. Thus, we can distinguish between an *incumbent-led incremental energy transition* in the UK and a *new-entrant-led disruptive energy transition* in Germany [83], the latter resulting in the first wave of electricity disruption. That said, many interviewees also highlighted high resistance to further cross-sectoral disruption in Germany, particularly in relation to e-mobility due to the strong automotive industry attempting to slow down further waves of disruption.

Another key finding from our interviews is that regulation is influenced more by wider (sometimes not directly related) policy and political commitments than by ostensibly targeted decisions [93]. Consideration, therefore, should be given to the extent to which the wider direction and rate of change in new business models or technological innovation are influenced by economic or technological constraints and decisions taken by cooperatives or particular firms. If attention is restricted simply to actors and forms of ownership that directly constitute the regulatory environments themselves, then key factors may be missed in understanding wider potentialities for disruption of the unleashing of new business models.

The relative timing of the transitions in Germany and the UK is a possible explanatory factor in how different dimensions of disruption are visible. Germany's low-carbon energy transition was kick-started in 1990 with influential policies to follow: technology-specific policies set in motion in 1990 and feed-in-tariffs enacted from 2000 onwards [95,94,133]. While the UK had introduced the Non-Fossil Fuel Obligation (NFFO), it had relatively little impact on the growth of new low-carbon generating capacity [134]. Given Germany's early lead, there is a sense that incumbent companies were caught off guard in terms of the momentous changes that have ensued [135]. Incumbents in the UK may have observed such changes and sought strategically, during 2010–2015, to preserve their position through significant lobbying activities.

Although the UK has not experienced the range of technical, ownership and actor, business model, or regulatory changes akin to the first electricity disruption in Germany, this has not affected its climate change mitigation targets. The Committee on Climate Change [136] reports that decarbonisation of the electricity sector has progressed well [136]. Indeed, if CO_2emissions reduction is the only criterion for judging an energy transition, then deeper forms of institutional 'disruption' may at least initially not be necessary. However, caution is needed here, since the cost-scale relationship in UK renewable energy resource curves are generally (and overall) significantly more favourable than those in Germany [137–140]. So, this may mean that – all else being equal – geophysical conditions may enable similar levels of progress to be made in decarbonising the UK electricity supply for a lower level of institutional disruption than in Germany [81]. If so, the degree to which this may be a factor will relate to the precise form of the resource curves and will be subject to change as the transition proceeds. Either way, however, the overall pattern suggests that multiple values and motivations are influential beyond just the rationale of reducing CO_2emissions. This relates again to issues of ownership and actors and questions regarding the democratic implications of climate change mitigation strategies.

The UK not experiencing a first electricity disruption akin to Germany does not necessarily mean that a second electricity disruption towards the empowerment of consumers, to advance more socially just energy transitions, is blocked. Indeed, the UK has progressed with digitisation through its ongoing Smart Meter rollout with the intention of putting consumers "at the heart" and in control of their energy and efficiency measures [141]. However, so far such efforts have been largely rhetorical beyond the installation of the meters [142,124]. Germany on the other hand is noted as being a laggard in this regard and so far Smart Meters are destined for big energy users rather than smaller consumers [143]. Thus, there is not necessarily a linear progression in the waves of disruption, and future action may not be constrained by an absence of certain forms of earlier disruption.

While disruption is certainly a buzzword that many governments are getting behind, critical thought should be given by policy makers regarding what is meant by disruption, what kind of disruption should be promoted on the basis of meeting environmental and social sustainability goals, and with what implications – and doing so by being guided by the distinction of its different dimensions. In particular, explicit attention needs to be paid to ownership and actors as well as business models and markets, because they link with social issues in the distribution of the benefits and costs of the energy transition and are, thus, of key importance to sustainability transitions. That is, ensuring diversity and supporting new actors may be a crucial, yet under-recognised, part of ensuring the social sustainability of energy transition processes. In addition, such actor diversity may also accelerate the achievement of the environmental targets set for energy transitions. Lockwood [144] notes the importance of supporting 'new constitutions' of actors to drive transition processes, where established actors are unlikely to alter practices at a sufficient pace to bring about system-wide change. Leaving old actors in place is, thus, likely to lead to resistance through lobbying that could derail low-carbon transition processes. In addition, disruption to the regulatory landscape through a greater diversity of actors involved in the policy process seems to be a crucial factor.

The kinds of comparative insights emphasised above highlight the value of exploring energy transitions through the lens of 'dimensions of disruption'. At an analytical level, the disruption lens lends itself to an efficient yet nuanced comparison of how energy transitions differ without recourse to the detailed narratives often utilised in sustainability transitions research. The disruptive lens can assist policy discussions that deliberate more carefully about, not only the rate of CO_2reduction that is required, but also how particular technological preferences and policy support can influence changes in ownership and business models, and vice versa. This opens up different constituencies to attend to and discuss, for example, what types of ownership and business models are desirable. A focus on the disruptive consequences of energy transitions can also contribute towards more foresight and planning in managing the wider effects of low-carbon energy transitions, and involving considerations of how certain actors may be harmed by transitions, and how to manage the negative consequences of transitions through specific policy responses.

It has been noted that more comparative work is needed in the field of socio-technical transitions beyond focus on single case studies [47]. Our approach exploring four dimensions of disruption offers a straightforward way of contrasting transitions in different contexts through the lens of disruption, which does not require tracing the precise sequence of events bringing about socio-technical change, often required in the co-evolutionary approaches related to the MLP. Thus, the conceptual approach here can be utilised to compare concisely how low-carbon transitions differ between contexts, and as a platform for interrogating policy processes leading to these differences [145]. Indeed, our analysis has shown that even in Europe there is great variation in how low-carbon transition is unfolding and specifically what kinds of system dimensions are being disrupted. The latter point emphasises the need for literatures on disruption, in turn, to be more attentive to socio-technical perspectives.

The more multifaceted and heterogeneous picture of disruption that emerges here in relation to just two rather similar countries on the global stage, urges caution over the visions of a homogeneous natural force emphasised by Seba [8]. The facts that clean energy and broader sustainability transitions are urgent and imperative and that there is an increasing buzz around the global potential of disruption [18,8], should not be allowed to inhibit appreciation for the importance of apparently inconvenient and messy levels of complexity and diversity [146]. There is a risk that neglect for these conditions may impede successful low-carbon transitions.

7. Conclusion and policy implications

In this article, we examined the status of low-carbon electricity transitions in Germany and the UK, in 2017, through four dimensions of system disruption – technology, actors and ownership, markets and business models, and regulation – derived from literatures on disruptive innovation and sustainability transitions. Drawing on 28 interviews, we found that, in Germany, disruption was viewed by some stakeholders present within a 'first wave' of electricity disruption, with changes not only in technology but also in ownership, business models, regulation and the emergence of new actors. In contrast, the UK interviewees felt that the British energy system was yet to experience systemic disruption, with discussions focusing around regulatory and technological issues. According to our interviews, Germany was expecting a 'second wave' of disruption in electricity and a 'new wave' of disruption through the coupling of sectors, such as electricity and mobility, in the near future, something rarely discussed for the UK.

The challenge raised by these issues for policy, with regards to the four dimensions of disruption, is that disruption as a buzzword is usually focussed on technology and economic considerations at the firm-level. However, our analysis reveals that more systemic forms of disruption in relation to ownership and actors and regulatory factors are also important considerations. Policy makers should therefore consider how 'new constitutions' of actors [144] are given suitable institutional space to be involved in the policy process to enhance the overall sustainability of a particular energy transition. Insights from the UK transition suggest that without disruption to the actor networks, other factors such as new business models may also struggle to emerge, if regulatory environments are still dominated by a more narrow set of incumbent players.

The approach taken in this paper offers a relatively clear but flexible means for comparing on a systemic level what actually constitutes disruption in particular contexts by explicitly differentiating between four dimensions of system disruption. It offers a middle way between co-evolutionary and complex socio-technical accounts, while maintaining the systemic vantage point that is missed in firm-focussed disruptive innovation literatures. In closing, we argue that empirically-driven comparative analysis may serve an important role in bringing about more clarity on how disruption is unfolding in different energy transitions. With the term disruption becoming ubiquitous in energy policy discussions, ensuring greater clarity in terms of what is meant by disruption in different contexts is an important move to ensure more robust policy discussions and empirically grounded policy interventions.

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