Energy Policy 149 (2021) 111984

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners

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ARTICLE INFO

Keywords:
Energy systems models
Scenarios
Foresight
Disruption
Discontinuity
Climate change mitigation

ABSTRACT

Scenarios may be qualitative or quantitative, the latter of which can be developed using energy systems models. This study explores how different energy systems models and scenarios explicitly represent and assess potential disruptions and discontinuities. The focus is on futures studies and forward-looking scenario and modelling exercises. We apply definitions of 'emergent' (uncoordinated) and 'purposive' (coordinated) disruption to a systematic review on how energy systems models and scenarios have been used to capture disruption and discontinuity. We first conducted a review of reviews of energy models and scenarios to provide an overview of their common classifications. Additional searches then sought studies which use different types of models and scenarios to explore disruption and discontinuity. We analyse a subset of 30 of these modelling or scenario studies in which authors self-identify and represent disruption or discontinuity, finding that the most frequently used methods were qualitative, exploratory foresight scenarios or agent-based models. We conclude that policy makers could prepare more effectively for social, economic and political disruption by integrating multidisciplinary insights from social and political sciences, engineering and economics through a broader range of methods: exploratory, foresight scenarios, simulation and agent-based models and repurposed energy systems optimisation models.

1. Introduction

The energy system is currently in a time of transition in the context of the Paris Agreement (UNFCCC, 2015) which sets out an aim to limit global warming to 1.5 °C above pre-industrial levels, in order to mitigate potential risks and impacts of higher temperature increases (IPCC, 2014; IPCC, 2018). Recent national laws and ambitions aim to reduce greenhouse gas emissions to net zero (CCC, 2019; ECIU, 2020; SEPA, 2019). However, the direction and pace of this energy system transition are uncertain due to the possibility of discontinuous change in a number of areas, from dominant technologies and the scale of the energy system, to governance, politics, institutional arrangements and lifestyle changes.

In 'The Age of Discontinuity', Drucker (1969) describes discontinuities as the shifts in the foundations of society which develop gradually and quietly, but inevitably lead to sudden events in which new technologies or institutions may replace existing ones. Ayres (2000) expands this definition by characterising discontinuities as having a high, irreversible impact or a high rate of change, depending on the timescale over which each discontinuity is perceived. According to Ayres, a 'high rate of change is one of the criteria for discontinuity. Another is the magnitude of the change, and its consequences. Unidirectionality or irreversibility is a possible third criterion.'

In this paper, we follow definitions of disruption and discontinuity set out by Burt (2007) which help to distinguish between the two concepts, and are consistent with Ayres' expanded criteria for discontinuity (Ayres, 2000). Burt makes a distinction between disruptions as temporary disturbances which do not cause fundamental change to the current state of order, and discontinuities which are unpredictable and irregular and do lead to fundamental change (Burt, 2007). While discontinuities may happen or develop at any time, they are a concern now because of the scale of transformation required to achieve deep decarbonisation of the energy system. Some disruptive technological innovation could help to accelerate progress towards meeting carbon reduction targets, whereas other social and political discontinuities may adversely impact the rate at which decarbonisation can be achieved. Disruptions and discontinuities also vary in terms of the spatial scale at which they take

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https://doi.org/10.1016/j.enpol.2020.111984
Received 17 September 2019; Received in revised form 29 September 2020; Accepted 12 October 2020
Available online 6 November 2020
0301-4215/

effect, from individual households (Wood, 2014), to national energy supply infrastructure (Chaudry et al., 2009), through to international and global disturbances such as pandemics, oil shocks and financial crises (Ayres, 2000; Mendonca et al., 2004, 2009).

We apply definitions of 'purposive' and 'emergent' disruption developed by Ketsopoulou et al. (2019), who set out that disruptive change is consistent with a significant variation from current trends, while continuity-based change supports continuation of existing trends. Ketsopoulou et al. contrast purposive disruption (where change is disruption-based and coordinated) with emergent disruption (where change is disruption-based and uncoordinated). This extends a typology of socio-technical transitions presented by Smith et al. (2005).

Examples of purposive disruptions relevant to energy systems include climate change mitigation policy, environmental regulation and organised environmental and social movements such as Extinction Rebellion (Extinction Rebellion, 2020). Some emergent disruptions may be technological in nature, such as rapid cost reductions in the capital costs of solar photovoltaics (PV) (Carrington and Stephenson, 2018). The Fukushima nuclear accident had far reaching, international impacts on nuclear energy policy, while also incentivising transitions to renewable energy sources in some countries (Heiligtag et al., 2017). In the UK, the rapid transition from the use of coal to natural gas for electricity generation in the early 1990s (known as the dash for gas) was precipitated by political events and the lifting of a European moratorium on natural gas-fired generation (Gross et al., 2018; Watson, 1997). Unpredictable political and societal discontinuities, such as the United States' decision to withdraw from the Paris Agreement in 2017, the UK's European Union membership referendum in 2016 or the profound impact and implications of the COVID-19 pandemic, are particularly difficult to anticipate or account for in long term energy systems planning.

1.1. Scenario planning and energy systems models: relevance to the study of disruption and discontinuity

Our study utilises the following definitions of scenarios and energy systems models in the literature. A scenario has been defined as a "plausible and often simplified description of how the future may develop" (IPCC, 2007). According to Durance and Godet (2010), a scenario "is not a future reality but rather a means to represent it with the aim of clarifying present action in light of possible and desirable futures." Similarly, scenarios can be thought of as "specific representations of the future to facilitate thinking about the possible consequences of different events or courses of action" (Wiebe et al., 2018, p. 547). In this paper, we consider a range of scenarios that may be qualitative, quantitative or a mixture of both, and may be developed through a process of expert, stakeholder or public consultation, or quantified using energy systems models (see Fig. 3 below).

Energy systems models are mathematical, computer models that are widely used in energy research, policy making and businesses to develop quantitative scenarios (Hall and Buckley, 2016). Quantitative modellers in effect 'choose' a particular scenario when they input initial conditions and parameters into a model, which is then used to add quantitative detail to that scenario. It is good practice for initial model inputs, parameters and assumptions to be explicitly acknowledged (e.g. in accompanying documentation and publications) and based on a clear scenario narrative.

Key drivers behind energy system change, such as changes in governance or industrial structures, can be unexpected, either because they cannot be captured through modelling and scenario tools, or there is an expert consensus that certain changes are not likely or plausible, leading to their exclusion from consideration in such tools (McDowall et al., 2014; Trutnevyte et al., 2016; Gambhir et al., 2019b). However, as a review of past UK scenario exercises by Trutnevyte et al. (2016) has shown, events and developments that were considered highly unlikely at the time a scenario was constructed, have happened.

Investors and policy makers use scenarios developed by 'authoritative' organisations such as the IEA or IPCC, and these scenarios in turn condition which future outcomes are considered to be plausible (Carrington and Stephenson, 2018). Prominent global energy scenarios, such as the IEA World Energy Outlook, have frequently underestimated solar PV learning rates and associated annual capacity increases over the last decade (Carrington and Stephenson, 2018; Mackenzie, 2017).

In the development of scenarios and futures analyses, thinking needs to be opened up to options or possibilities which may be hidden by mainstream or dominant views, such as potential shocks (P. W. F. van Notten et al., 2005; Volkery and Ribeiro, 2009). Promotion of a small number of standardised scenarios, for example by the IPCC, carries the risk that multiple potential discontinuous futures are not considered (Wiebe et al., 2018).

Neuroscientific evidence indicates that humans lack capacity to imagine future developments that deviate significantly from current and historic trends (Beck, 2017; Gambhir et al., 2019b; Mullally and Maguire, 2014). This is compounded by 'groupthink' in which expert

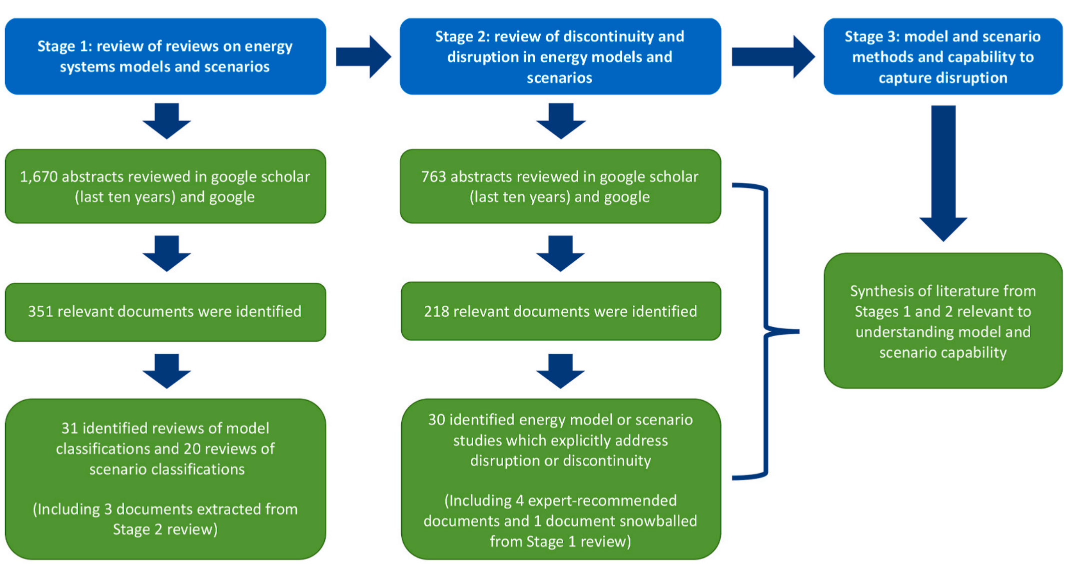

Fig. 1. Systematic review method: process chart.

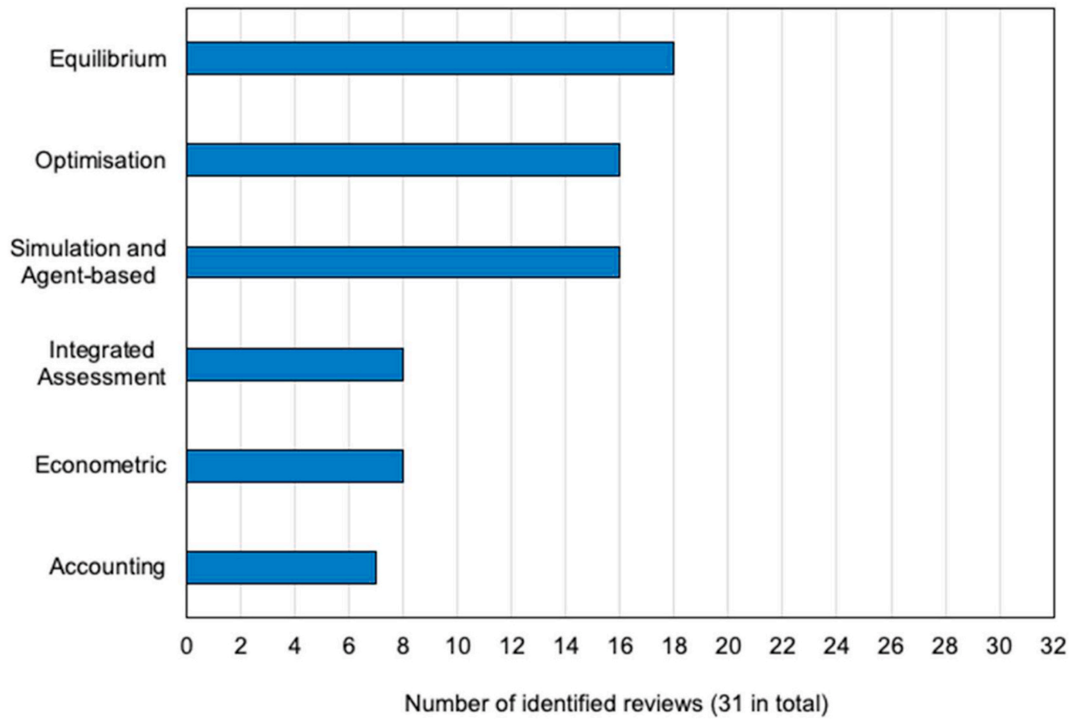

Fig. 2. Number of reviews identifying specific categories of energy systems model methods (total 31 reviews).

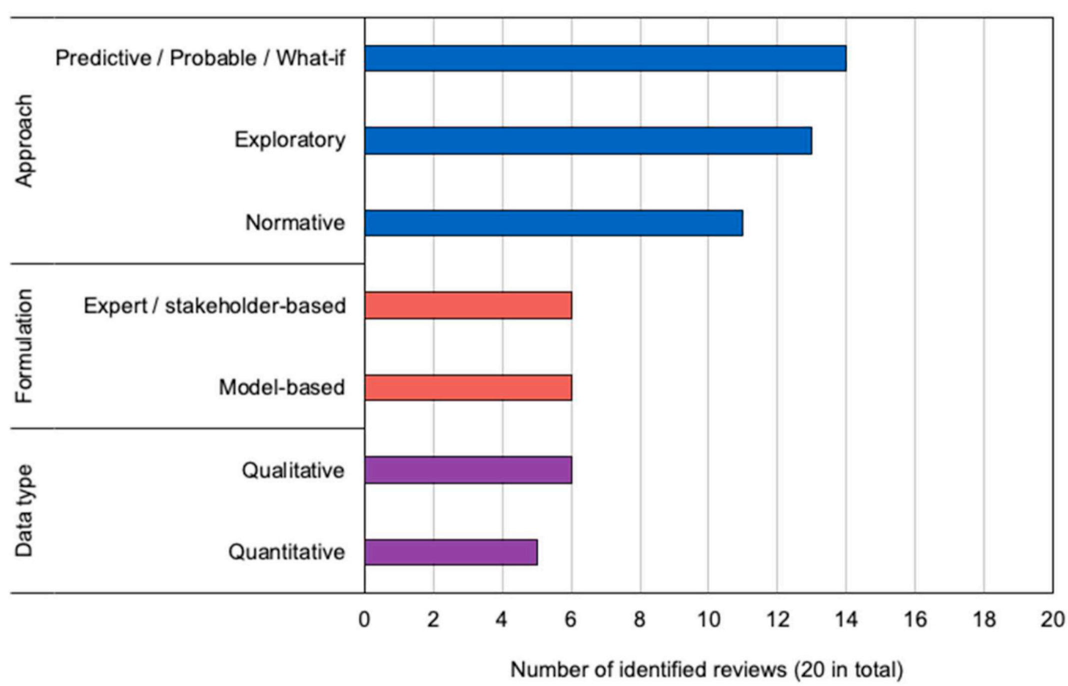

Fig. 3. Number of reviews identifying specific categories of energy scenario approaches, formulation and data (total 20 reviews).

communities tend to avoid conflict, converge upon accepted ideas and norms due to a lack of critical challenge, and inability or unwillingness to consider scenarios with undesirable, complex or high risk consequences (Janis, 1972; Gambhir et al., 2019b). In this context, Funtowicz and Ravetz (1993) call for "post-normal science" and an extended peer community involving new participants and stakeholders from non-expert perspectives who are provided legitimacy to quality assure scientific inputs, helping to democratise scientific knowledge.

1.2. Disruption and discontinuity in energy systems models and scenarios: contribution to the literature

There are limited examples in the literature of systematic reviews seeking to identify how energy systems modelling and/or scenario studies aim to represent and analyse disruption or discontinuities. Extensive research has been carried out by Sirkka Heinonen and colleagues on the role and application of explorative, foresight scenarios in capturing emergent and hard to anticipate discontinuities (e.g.

Heinonen, 2015; Heinonen et al., 2017a; 2017b; Heinonen and Ruotsalainen, 2013). Layzell and Beaumier (2018) consider the capabilities of different types of energy systems models used by the government and private sector in Canada. Layzell and Beaumier find that many energy systems models (e.g. optimisation or economic equilibrium models), are capable of assessing the implications of climate change policies. However, fewer models can provide satisfactory insights into how 'transformative or even disruptive technological, business or social innovation' can be influenced in order to support societal objectives such as climate change mitigation (Layzell and Beaumier 2018). McCollum et al. (2020) contend that prominent energy models used in energy and climate policy scenarios are structurally limited in their ability to account for unexpected extremes and 'out of the ordinary' events. One potential solution is the use of "off-model" tools (e.g. spreadsheet models, econometric, stakeholder participation) for quantitative scenario building in addition to the core energy model (McCollum et al., 2020).

van Notten et al. (2005) examine different scenario studies according to the extent to which they address discontinuity. The scenarios considered in this study relate to a wide range of themes (not specifically energy), e.g. transport, nutrition, gender equality, the labour market and climate change. Van Notten et al. select 22 scenarios for analysis 'from a broad set of approximately 70 studies based on the detail of the available documentation,' and differentiate between those scenarios which explicitly incorporate discontinuity and those which do not (i.e. they omit various terms relating to discontinuity).

In our paper, we build on van Notten et al.'s study by:

- analysing a larger sample of energy systems modelling and scenario exercises which explicitly represent discontinuity or disruption;
- focusing on energy systems models and scenarios in the energy sector (while also including scenarios in other sectors);
- considering how discontinuity and disruption are represented in a range of more recent energy systems models and scenarios.

1.3. Research aims

This paper sets out to explore how disruption and discontinuous change has been represented in a range of energy systems modelling and scenario studies. Findings are presented from a systematic evidence review which identifies examples of energy systems model and scenario use in the literature where authors explicitly use terms such as "disruption", "discontinuity" or similar to refer to phenomena being modelled or included in a given scenario narrative. We further draw upon relevant literature where these terms are not explicitly used to evaluate model and scenario capabilities to capture disruptive changes. The focus of this paper is on futures studies and forward-looking scenario and modelling exercises, rather than studies that try to replicate or explain the past.

The evidence review addresses the following overall question:

- How have different types of disruption and discontinuity been explored explicitly by a range of energy systems model and scenario methods?

The review has then sought information on the relationships between modelling/scenario approaches and the ability to represent disruption and discontinuity, addressing the following subsidiary questions:

- Are particular model/scenario approaches or techniques better suited to exploring specific types of disruption or discontinuous change?
- How do the structure and frameworks of energy systems models and scenarios affect their capability to capture disruption and discontinuity?

This paper is structured as follows. Section 2 outlines the systematic review methodology used in this study. Section 3 considers different types of energy models and scenarios and their capability to capture disruptive or discontinuous change in energy systems. Section 4 presents results on studies extracted from the review which self-identify disruption and discontinuity in a modelling or scenario analysis. This section explores how different types of disruption or discontinuity are represented in these studies. Section 5 concludes and discusses implications of the findings for policy and practitioners.

2. Methodology: systematic review approach

In this study, we have carried out a systematic review of academic and grey literature on how energy systems models and scenario studies self-identify and represent discontinuous changes and disruption in energy systems. This comprised three stages (Fig. 1). The first stage of the systematic review comprised a widely-scoped review of the scenario and modelling literature in order to provide an overview of the range of modelling approaches and scenario types used in energy systems model and scenario exercises. This was delivered through a systematic review of reviews, drawing upon review of review approaches in medical and healthcare literature, in which search terms are developed to reveal review papers and meta-analyses (Abraha et al., 2017; Montori et al., 2005; Smith et al., 2011). Similar to Montori et al. (2005), we considered a document to be a review if it included words such as "review" or "meta-analysis" in the title or abstract - see full list of search terms in Appendix A (Table A.1) - or if the main body of the text reviewed or summarised literature on different categories of energy systems models and/or scenarios.

The second stage of our systematic review involved more focused searches in the energy literature which sought information on the use of different models and scenarios in studies which explicitly explore disruption or discontinuity. A third stage entailed synthesis of relevant literature extracted during the first two stages, in order to evaluate the capability of energy systems models and scenarios to capture disruption or discontinuity in energy systems (Fig. 1).

The search terms applied in the first two stages of the review, description of the search databases used (Google scholar and google), and criteria for identifying and rating relevant documents, are set out in Appendix A and Tables A.1 and A.2. Relevant documents identified through the first two stages were combined with expert-recommended studies to evaluate the capability of different model and scenario structures/frameworks to capture disruption in energy systems. A small expert group was formed to advise on the design, methodology and findings of the review (Appendix B).

Fig. 1 summarises the number of relevant documents identified in the first two stages of the review. For the review of reviews, 1670 search results were reviewed in total: 1250 abstracts reviewed in google scholar and 420 in google. The search in google scholar was constrained to the last ten years, in order to capture relatively up to date classifications of energy models and scenarios - since the review studies identified refer to some documents published prior to 2008. The search in google did not allow the range of publication years of documents to be constrained. In total, 351 relevant documents were identified, of which 137 were assigned relevance rating 1, and 186 relevance rating 2 (Fig. 1). An inspection of all the relevance rating 1 documents revealed 31 review or meta-analysis studies which categorised different types of energy systems models, and 20 studies which identified and reviewed various scenario categories (Table A.3 in Appendix C). The purpose of this first stage of the evidence review was to collect information on types of models and scenarios which would help to categorise modelling and scenario studies of disruption and discontinuity in the subsequent part of the research.

In the second part of the evidence review, 763 search results were inspected in total: 400 abstracts reviewed in google scholar and 363 documents reviewed in google. The search in google scholar was limited to the years 2000–2018, since the focus of this study is on the capability of relatively recent energy model and scenario tools. From these, 218 relevant documents were identified, with 59 assigned relevance rating 1 and 120 relevance rating 2 (Fig. 1). The relevance rating 1 documents were examined in depth to isolate those studies which self-identify and investigate different types of disruption or discontinuity and include sufficient information about the energy systems models or scenarios which they use. We selected a subset of 30 of the relevance rating 1 documents in which authors self-identified or declared their intention to investigate disruption and/or discontinuity in energy models or scenarios. A range of keywords relating to disruption and discontinuity, drawn from the search terms, were used to diagnose models or scenarios which explicitly represented disruption across the relevance rating 1 documents (see Table A.4 in Appendix C).

Three documents were identified in the Stage 2 review which carried out reviews or meta-analyses of energy systems model/scenario types. These were included in the final set of documents for Stage 1. One study was selected for analysis in Stage 2 by snowballing (Greenhalgh and Peacock, 2005) from a document identified in Stage 1 which cited a scenario study explicitly representing disruption. In addition, four documents in Stage 2 were identified from expert recommendations, including via the expert group (Appendix B). The following two sections consider the findings from the evidence review.

3. Typologies of energy systems models and scenarios and capability to represent disruption and discontinuity

As set out above, we identified 31 documents which categorise different types of energy systems models, and 20 studies which reviewed various scenario categories. Typologies and categories of energy systems models and scenarios (Tables 1 and 2) were gathered from the identified review of reviews, and the most commonly occurring categories are shown in Figs. 2 and 3. This carries an important caveat that there is much variation in categories identified in the literature, and there is a large degree of crossover between the typologies shown here, which are not necessarily mutually exclusive. A more comprehensive classification of energy systems models, based on 14 different types of categorisation, is available in Hall and Buckley (2016). Different typologies of scenario methods are described by Börjeson et al. (2006) and Bradfield et al. (2005).

3.1. Identified typologies of energy models and scenarios

The analytical approach of energy systems models is classified commonly as 'Bottom up' or 'Top down' (Benichou and Mayr, 2014; Hall and Buckley, 2016; NREL, 2017), with these terms used in 65% and 58% respectively of the 31 identified reviews of model types. Bottom up models focus explicitly on technological opportunities for a given sector within the wider economy, and can analyse a range of policy options and impacts on cost and emissions. Top down models use historical variables to assess economy-wide responses to policies or other stimuli (Benichou and Mayr, 2014; Hall and Buckley, 2016; NREL, 2017). 12 of the 31 identified reviews refer to 'Hybrid' models which combine elements of both bottom up and top down models, either by coupling (soft-linking) them or by integrating them in a single model (hard-linking) (Andersen et al., 2019; Hall and Buckley, 2016; Krook-Riekkola et al., 2017).

Fig. 2 shows the most frequently occurring categorisations of model methodologies, of which 'Equilibrium', 'Optimisation' and 'Simulation and Agent-Based' featured in at least half of the reviews. These common methods of energy systems models are defined in Table 1 above. Within the category 'Equilibrium', partial equilibrium models follow a 'Bottom up' approach and computable general equilibrium (CGE) models use a 'Top Down' approach (NREL, 2017). Integrated assessment models, econometric and accounting methodologies featured to a lesser extent across the review documents (Fig. 2).

With respect to scenarios, the 20 documents identified in the review

Table 1
Prominent energy systems / energy-economy models: definitions and common examples in the literature[a].

Energy systems/ energy-economy model type	Description	Common examples/typologies
Optimisation and partial equilibrium models	Optimisation models can be used to identify an optimal technology mix, accounting for system constraints and based on minimising a value such as cost, emissions, fuel use or in some cases, maximising return on investment. Partial equilibrium models only achieve equilibrium in some economic sectors. Many energy systems optimisation models also use a partial equilibrium approach.	Energy systems optimisation models e.g. MARKAL; TIMES; MESSAGE; ESME; OSeMOSYS.
Computable general equilibrium (CGE) models	Computable general equilibrium (CGE) models can be used to study the whole economic system. They set out to achieve equilibrium simultaneously in supply and demand across all economic sectors, including the energy sector.	UKENVI; EPPA.
Simulation models	Simulation models attempt to reproduce and represent the operation of a system. They can simulate the behaviour of energy producers and consumers in terms of how they respond to price and income signals. Traditional simulation models describe changes in a variable state and use differential equations to capture changes in state. State changes then inform further differential equations which are solved continuously. This approach allows systems behaviour such as feedback to be incorporated.	World Energy Model (Shell); EnergyPLAN.
Agent-based models	Agent-based models represent a complex evolving system in which multiple, heterogenous agents (e.g. companies or households) interact and give rise to emergent properties which would not otherwise result from simple aggregation of agents' individual properties. Agents are represented by behavioural algorithms which govern and condition the logic under which agent behaviour changes through continuous interaction or in response to events.	NEMS; PRIMES. Both models have a hybrid modular structure, incorporating different modules which may use agent-based, simulation or optimisation methods.
Econometric models	Econometric methods attempt to model future behaviour by deriving statistical relationships from past behaviour. Econometric models can be based on models of	Econometric models of energy demand, e.g. BEIS Energy Demand Model (UK). Macro-econometric models, e.g. E3ME.

(continued on next page)

Table 1 (*continued*)

Energy systems/ energy-economy model type	Description	Common examples/typologies
	deterministic or stochastic economics.	
Accounting models	Accounting models are typically simple and transparent representations of key performance characteristics of an energy system, e.g. supply, demand and greenhouse gas emissions. They may use spreadsheet software, such as Excel. They enable users to understand implications of decisions relating to climate change mitigation policy, the environment, resources, and social costs.	LEAP; DECC 2050 Energy Calculator.
Integrated Assessment Models (IAMs)[b]	IAMs combine representation of natural, physical processes (e.g. atmospheric and sea-level) and socio-economic systems, including energy, agriculture and land use systems. IAMs have been used extensively to evaluate potential strategies for, and costs of, climate change mitigation and adaptation over the 21st Century. In this respect they may follow a least-cost optimisation or detailed macro-economic approach.	IAMs used in development of shared socio-economic pathways (SSPs) for the Intergovernmental Panel on Climate Change (IPCC): IMAGE; MESSAGE-GLOBIOM; AIM/CGE; GCAM; REMIND-MAgPIE; WITCH-GLOBIOM. Macro-economic based IAMs, e.g. RICE; DICE.

[a] Table sources: Gambhir et al. (2019a); Hall and Buckley (2016); Karjalainen et al. (2014); Koppelaar et al. (2016); Lamperti et al. (2018); Pfenninger et al. (2014); Pye et al. (2018); Sue Wing (2006, 2009).

[b] Integrated Assessment Models (IAMs) are not strictly a separate category – they may for example utilise optimisation or economic equilibrium methods. IAMs are nevertheless included in Table 1 since they are discussed frequently as a model class in the literature.

of reviews varied in terms of whether they classified scenarios in the energy sector, or scenario planning more generally. A wide variety of scenario definitions and methodological categories have been described in the literature, and these are sometimes contradictory (Bradfield et al., 2005; Trutnevyte et al., 2016). In Fig. 3, relevant studies which classified typologies of scenarios most commonly made a distinction between predictive, exploratory and normative scenarios. These typologies, defined in Table 2 above, were used to classify scenarios in over half of the identified review documents, although alternative classifications were used in a smaller number of studies. These include the 'intuitive logics' approach which is qualitative, process-based and can be considered exploratory or normative, and 'probabilistic modified trends' scenarios which aim to enhance traditional, extrapolative forecasts and combine quantitative methods with qualitative components (Amer et al., 2013; Bradfield et al., 2005; Derbyshire and Wright, 2017; Trutnevyte et al., 2016). Several reviews in Fig. 3 also categorised scenarios in terms of their data (qualitative or quantitative) and formulation (developed through consultation with experts, stakeholders or members of the public, or generated from models).

3.2. Capability of energy systems models and scenarios to represent disruption and discontinuity

Section 4 presents findings from the second stage of our systematic

Table 2
Prominent energy scenario types: definitions and common examples in the literature.

Energy scenario type/ approach[a]	Purpose	Common sub-categories[b]	Common examples
Exploratory (possible) scenarios	Address the question "What can happen?" (Börjeson et al., 2006, p. 727)	*Exploratory external* – assume that current policies remain constant, and assess resilience to the evolution of external events (e.g. natural or societal). *Exploratory strategic* – incorporate endogenous decision making and test the consequences of different policies and strategies, accounting for external variables.	Foresight scenarios and Futures Cliniques, e.g. Rohrbeck and Schwarz (2013); Heinonen (2015). Wild card management systems, e.g. Mendonça et al. (2009). Stress tests, e.g. Heiligtag et al. (2017).
Normative (target-setting) scenarios	Address the question "How can a specific target be reached?" (Börjeson et al., 2006, p. 728)	*Normative preserving* – assess how a target can be efficiently met within existing system structure and assuming continuity of socio-economic variables. *Normative transforming* (e.g. using optimisation models) – address which existing structures, e.g. societal and policies, need to change in order to meet a target efficiently.	Normative, cost-optimal pathways to climate change mitigation developed using energy systems optimisation and/or integrated assessment models (Pfenninger et al., 2014; van Exter, 2017). Backcasting scenarios (Börjeson et al., 2006). Intuitive logics (Derbyshire and Wright, 2017).
Predictive (probable) and what-if scenarios	Address the question "What will happen?" (Börjeson et al., 2006, p. 726)	*Predictive forecast* – focus on a single, most likely scenario. *Predictive what-if* – assess how two or more scenarios unfold in response to a future, significant near-term event which acts as a bifurcation point.	Traditional forecasting - extrapolation of historic trends, e.g. time series analysis (Amer et al., 2013). Probabilistic modified trends (Bradfield et al., 2005). What-if scenarios (Börjeson et al., 2006).

[a] Hybrid qualitative/quantitative approaches entail the integration of qualitative scenarios and quantitative energy systems models. An example of this approach is "story and simulation", whereby qualitative storylines are linked with quantitative models (Alcamo, 2008).

[b] Sources for "Common sub-categories" column: Börjeson et al. (2006); Koppelaar et al. (2016); Trutnevyte et al. (2014); Trutnevyte et al. (2016).

review on how existing modelling and scenario studies have represented disruption and discontinuity. Here, in this section, we draw upon the synthesis of literature from the first two stages of the systematic review, as illustrated in Fig. 1.

We consider different modelling and scenario methods identified above, in terms of their capability to capture disruptive change which may affect the progress of climate change mitigation or adaptation efforts. This carries the caveat that we do not intend to make more general judgements about the relative insights that different energy models or scenarios can offer.

In sections 3.2.1 to 3.2.4, we focus on the most frequently identified categories of energy systems models in our review of reviews:

optimisation, economic equilibrium, simulation and agent-based models (Fig. 2). We also consider Integrated Assessment Models (IAMs), which may use optimisation or economic equilibrium methods, because they are often discussed as a modelling class in the literature particularly with respect to global climate change mitigation policy (Gambhir et al., 2019a; van Sluisveld et al., 2018; Wilson et al., 2018).

While energy systems optimisation models and IAMs are strong at representing technologies in high levels of detail, their use tends to focus on energy supply-side options and is limited in representing how demand-side policies and non-technological changes (i.e. economic, social and behavioural) can reduce energy demand (Hardt et al., 2019; Wilson et al., 2018). This supply-side focus is a feature of climate change mitigation research and prevalent techno-economic scenarios more generally (Creutzig et al., 2018).

A general criticism of energy systems models is that their structural complexity and numerous input parameters and variables render them a 'black box' for non-modellers who lack specialist programming knowledge (Böhringer et al., 2003; Gambhir et al., 2019a; Sue Wing, 2004). As noted in section 1.1, energy systems models are quantitative tools used to produce quantitative scenario outputs. The capability of different scenario approaches, and hybrid approaches which attempt to link qualitative scenarios and quantitative models, are discussed in sections 3.2.5 and 3.2.6.

3.2.1. *Energy systems optimisation models*

Climate change mitigation scenarios used by energy and climate policy makers are largely generated from energy systems optimisation models, for example MARKAL, TIMES and ESME in the UK (DeCarolis et al., 2017; Hall and Buckley, 2016; Pye et al., 2018; Taylor et al., 2014). Conventional energy systems models based on cost-optimal combinations of low carbon energy technologies and perfect, uninterrupted decision making over a long planning horizon can help policy makers understand how to achieve long-term decarbonisation targets. These models may imply rapid disruptive changes in energy systems, business models and user practices. In traditional, perfect foresight energy systems models, significant transitions occur either exogenously, through assumed discontinuities such as technological breakthroughs, or through perfect implementation of policies (Lamperti et al., 2018; Shchiptsova et al., 2016). Since perfect foresight models assume optimal policy implementation over extended time periods, they tend not to account for unpredictable, discontinuous events relating to governance, wider social and political changes which may adversely affect the progress of carbon abatement policies. Nevertheless, perfect foresight approaches can be modified to capture some discontinuous events by using myopic or partial foresight versions of energy systems optimisation models. Myopic or partial foresight optimisation models allow shorter planning time horizons to be considered in successive time steps, so that later time steps can incorporate discontinuities such as technological breakthroughs (Fuso Nerini et al., 2017; Gils, 2018; Heuberger et al., 2018).

Techniques for accounting for uncertainties in energy systems models may help to overcome some of the limitations associated with cost optimal scenarios which assume perfect foresight (Trutnevyte, 2016). Energy systems optimisation models may be subject to parametric uncertainties, such as poor knowledge about empirical values for input parameters, or structural uncertainties, for example in equations governing model structure (Pfenninger et al., 2014; Yue et al., 2018). Yue et al. (2018) present three different techniques for addressing parametric uncertainty in energy systems optimisation models: Monte Carlo Analysis (MCA), stochastic programming and robust optimisation.

In Monte Carlo Analysis (MCA), uncertain input parameters are varied across a range of values based on probability distributions obtained from the literature, expert elicitations or modellers' judgement. MCA still uses perfect foresight but attempts to capture multiple outcomes to provide coverage of uncertainty. The model is run hundreds of times typically for each set of input parameters. Whereas in MCA each scenario generated is assumed to be equally probable, stochastic programming presents a single course of action that "hedges" against multiple future uncertainties. However, both MCA and stochastic programming require large amounts of computational power and can be impractical to apply to large, complex energy systems optimisation models. As an alternative, robust optimisation can provide a means of evaluating how robust different hedging strategies are under uncertainty, while involving a lower calculation burden (Yue et al., 2018).

In contrast to the above three techniques, modelling to generate alternatives (MGA) can help to account for structural uncertainties in energy systems optimisation models. MGA does this by searching for 'near optimal' solutions, rather than the most optimal solution, which may be feasible given unforeseen and unmodelled risks. This can help decision makers choose alternative strategies which are more relevant to policy concerns than the optimal option, and test these policy strategies against multiple, near optimal scenarios (Trutnevyte, 2016; Yue et al., 2018). Such an approach of systematically exploring near-optimal scenarios could be used as a 'bounding analysis' to explore boundaries of uncertainty in scenarios of future energy transitions (Trutnevyte, 2016). MGA is however, only a limited means of addressing structural uncertainties in models, and approaches which combine insights from different model structures and/or scenario types (see section 3.2.6) also have value in this respect (Yue et al., 2018).

3.2.2. *Computable general equilibrium (CGE) models*

Computable general equilibrium (CGE) models set out to achieve a simultaneous equilibrium of supply and demand across the complete economic system, including the energy sector (Hall and Buckley, 2016; Sue Wing, 2009). They are widely employed to understand the distributional and welfare impacts of fiscal policies such as taxes and subsidies (Sue Wing, 2004), and have been used to analyse the effects of energy and climate policies across multiple markets (Sue Wing, 2006, 2009).

CGE models are not suited on their own to analysis of dynamic change: they are typically rigid in attaining economic equilibrium around one base year, and the initial baseline parameters will influence the economic representation of modelled futures. Dynamic economic change can be captured by inputting exogenous variables into a CGE model, e.g. from another model (Mitra-Kahn, 2008). Conventional approaches to representing technological change in CGE models serve to slow projected rates of diffusion (Morris et al., 2019). In comparison to technology-rich, optimisation models which focus on the energy system in a partial equilibrium approach, representation of endogenous technological change is more limited in CGE models (Köhler et al., 2006), which expend much of their computational power on balancing supply and demand across economic sectors. For these reasons, 'hybrid' modelling methods have sought to combine the top-down, whole economy equilibrium approach of CGE models with bottom-up, technologically detailed energy systems optimisation models (Andersen et al., 2019; Krook-Riekkola et al., 2017; Sue Wing, 2006).

CGE models simulate the effect of a small number of 'representative agents' on macroeconomic output. Representative agent models do not capture the behaviours of multiple, heterogenous agents or interdependencies between them. These models have been associated with a failure to anticipate the global financial crisis (Sherwood et al., 2017).

3.2.3. *Integrated assessment models*

Full-scale Integrated Assessment Models (IAMs) can be used to explore how climate change mitigation can be achieved at least cost, for example by adding quantitative detail to shared socio-economic pathways (SSPs) for the Intergovernmental Panel on Climate Change (IPCC) (Gambhir et al., 2019a; O'Neill et al., 2017). Reduced-form, macro-economic based IAMs, such as RICE and DICE, permit a cost-benefit analysis of limiting greenhouse gas emissions (Nordhaus, 1993; Nordhaus and Yang, 1996).

With respect to characterising disruptive events, IAMs are subject to similar limitations as discussed in the previous two sections. IAMs may incorporate optimisation or economic equilibrium approaches and assume a single, rational decision maker with perfect foresight. The latter is a key limitation in comparison to agent-based models which are discussed in the following section, and enable the study of heterogenous decision makers who can adapt in different ways to the economic impacts of climate change (Lamperti et al., 2018).

Given their global scale and operation over multiple decades, IAMs lack the computational power to represent energy systems at high levels of geographic or temporal detail (Gambhir et al., 2019a; Pfenninger et al., 2014). The granularity of IAMs is too coarse to adequately capture geographically dispersed, intermittent renewable electricity technologies (Gambhir et al., 2019a), or multiple, small-scale, heterogenous end-use energy technologies (Wilson et al., 2018).

Innovation and diffusion of low-carbon technologies are frequently over-simplified in IAMs and large energy systems models, for example with respect to differences between regional and global learning and experience curves (Gambhir et al., 2019a; Remme, 2018). Bottom up, technology-rich energy systems models using modelling frameworks such as MARKAL and TIMES (e.g. TIAM – the TIMES Integrated Assessment Model) have typically represented technology cost reductions and learning using exogenous forecasts (Anandarajah et al., 2013). These exogenous forecasts may be sourced widely (including from learning curve studies) and bring in their own external assumptions about the deployment rates of particular technologies. Importing learning curve data into models has the disadvantage that the investment costs of initially expensive new technologies may be understated if they are not deployed until subsequent years when they have become sufficiently cheaper. An alternative approach is endogenous technology learning (ETL), whereby learning costs are integrated into the model structure and can be captured more holistically within the system being modelled. This allows a technology to be selected even if it might not be the least-cost option at a given time, since it may undergo learning that can then be applied to other products or innovations in technology clusters (Anandarajah et al., 2013).

Outdated input data on capital costs and market trends have contributed to rates of technological learning or cost reduction being underestimated in IAMs; moreover, input cost data can become quickly out-of-date where a technology such as solar PV experiences rapid learning (Carbon Tracker and Grantham Institute, 2017; Gambhir et al., 2019b). Conversely, in order to achieve 2 °C climate change stabilisation targets, IAMs may solve to unprecedented rates of future technology deployment, e.g. average annual solar PV and wind power capacity additions, which exceed historically observed rates for the diffusion of technologies (Napp et al., 2017; van Sluisveld et al., 2015).

1.5 °C transformation pathways based on global IAMs mainly incorporate currently available low carbon substitute technologies, and in addition normally require negative emissions technologies or reduced demand-side emissions to achieve a 1.5 °C target (Gambhir et al., 2019a; Wilson et al., 2018). There is a need for 1.5 °C transformation pathways to explore the contribution of 'disruptive low-carbon innovations', i.e. business models and technologies which provide novel goods and services for consumers, with potential to commercialise rapidly and lower greenhouse gas emissions if adopted widely. Examples of such disruptive innovations include: solar PV combined with storage and peer-to-peer electricity trading; the internet of things and home energy management systems; mobility-as-a-service, electric vehicles and vehicle-to-grid (Wilson et al., 2018).

Grubler et al. (2018) develop and present an alternative global climate change mitigation scenario called 'Low Energy Demand'. This makes use of the global integrated assessment model MESSAGEix-GLOBIOM and a 'Low Energy Demand' global scenario. The low energy demand in the presented global scenario results in faster supply-side and end-use decarbonisation, without the need for negative emissions technologies. The scenario narrative incorporates rapid social and institutional changes which reverse the historical trend of rising energy demand. A key challenge for further research is how to improve the endogenous representation of such social and institutional changes in IAMs and energy systems models in general (Grubler et al., 2018).

3.2.4. Simulation and agent-based models

Similar to CGE models, simulation and agent-based models have a relatively low level of technological detail since their computational power is used up in other functionalities. Simulation models can be subdivided into two separate classes: differential equation and agent-based models (Koppelaar et al., 2016). Differential equation models were developed in the 1970s for electricity systems and allow systems behaviour to be flexibly incorporated. Agent-based models were applied to electricity systems from the 2000s (Koppelaar et al., 2016).

Agent-based models can simulate the interaction and adaptive behaviour of multiple agents (e.g. companies or households) operating under limited knowledge of future events and myopic decision making (Ehlen and Scholand, 2005; Klein, 2017; Lamperti et al., 2018). Simulated agents can therefore be disrupted by events which they cannot foresee (in contrast to perfect foresight models), and their behaviour can change dramatically and irreversibly as a reaction to small shocks (Lamperti et al., 2018; Sherwood et al., 2017).

Agent-based models can also be used to simulate how economic infrastructures recover in response to disruption, and point to path dependencies whereby an infrastructure system is not able to return to its initial state, instead following alternative (more or less optimal) paths (Ehlen and Scholand, 2005). This can help to understand how economic systems may shift from relatively stable states to continuous, out-of-equilibrium states, as a result of unexpected or stochastic shocks which emerge endogenously through the interaction of many different agents (Lamperti et al., 2018).

3.2.5. Scenarios: predictive, exploratory and normative

The reviewed literature reveals a number of general points about the capability of different qualitative or quantitative scenario approaches (broadly categorised as exploratory, normative and predictive, as set out in Table 2) to capture disruption in energy systems. Predictive scenarios attempt to anticipate future events or assess their probability of occurrence. Predictive forecast scenarios are generally not well suited to evaluating surprising events, since they typically describe a future based on the extrapolation of historic trends, leading to self-fulfilling outcomes (Börjeson et al., 2006; van Exter, 2017). Nevertheless, predictive what-if scenarios can potentially represent disruption because they compare alternative developments which follow a significant, near future event. This event could be a policy-led or emergent, surprising change, and acts as a bifurcation point from which system response can in principle, be assessed (Börjeson et al., 2006).

Exploratory scenarios examine the possibility rather than the probability of future events (Börjeson et al., 2006; van Exter, 2017). There are some similarities between predictive what-if and exploratory scenarios, however the latter usually have a longer time horizon and start typically at a point in the future (rather than the present as with what-if scenarios). There are two main sub-categories of exploratory scenarios: external and strategic (Table 2). Exploratory external scenarios assume that current policies remain the same and investigate the evolution and impact of external events, in order to help develop policies and strategies which are resilient to those events. Conversely, exploratory strategic scenarios can be used to test the consequences of different polices and strategies in relation to the evolution of future events (Börjeson et al., 2006). External scenarios are more suited to analysis of emergent and exogenous forms of disruption, whereas strategic scenarios have value in understanding the impact of purposive (co-ordinated) disruption and endogenous decision making.

A prominent example of exploratory scenarios are those produced by Shell, who pioneered the practice of corporate strategic foresight in the 1970s (Wilkinson and Kupers, 2013). The corporate foresight approach helps to "capture value through (1) an enhanced capacity to perceive change, (2) an enhanced capacity to interpret and respond to change, (3) influencing other actors, (4) and through an enhanced capacity for organizational learning" (Rohrbeck and Schwarz, 2013). Foresight techniques have been used both in the corporate sector and beyond, and they have been applied in particular to understand emergent and less anticipated discontinuities through the use of wild card management systems, stress tests or futures cliniques (see section 4 below). Wild card management systems can draw upon scenario or Delphi survey methods and involve scanning business and societal landscapes for weak signals of 'trend-breaking crises', in order to produce outlines of major changes which might occur in the future (Mendonça et al., 2009). Stress testing is a form of scenario planning that has been implemented in the banking sector, and attempts to identify previously overlooked extreme, low probability risks, estimate the extent of their potential impacts, and the resilience of corporate strategies to respond to them (Heiligtag et al., 2017). The *Futures Clinique* implemented by the Finland Futures Research Centre is a participatory workshop process which aims to identify potential disruptions by 'promoting futures thinking, futures preparedness and provocative futures dialogue' (Heinonen, 2015).

Normative scenarios focus on how a specific target can be reached, and can be divided into two common sub-categories: preserving and transforming (Table 2). Preserving scenarios aim to meet a target efficiently and assume that the existing system structure and key socio-economic variables remain the same (Börjeson et al., 2006). One example is the development of cost-optimal pathways to climate stabilisation using Integrated Assessment Models (van Exter, 2017). These pathways may imply disruptive technological innovation since they explore which mix of new technologies may be needed to achieve climate mitigation. On the other hand, they do not directly assess potential unanticipated socio-economic changes.

The second type of normative scenarios (transforming) are more appropriate for understanding directed, policy-led disruption and systemic change required to mitigate climate change. Transforming scenarios evaluate which changes to existing societal and political structures may be needed to meet a target efficiently (Börjeson et al., 2006). This approach is exemplified by backcasting scenarios, which explore how to break from current trends in order to reach a specific target (e.g. constraining to a global 1.5 °C temperature rise). The priority of transforming scenarios is the attainment of the final goal, as opposed to achieving it in the most cost-optimal way (although cost-optimisation may still be one consideration) (Börjeson et al., 2006; van Exter, 2017).

3.2.6. Hybrid approaches: linking qualitative scenarios and quantitative models

Koppelaar et al. (2016) outline how the different sub-categories of predictive, exploratory and normative scenarios, defined in Table 2, can be used for energy systems model problem analyses. There is however a lack of consistency in terms of how qualitative scenario-based inputs are incorporated within quantitative energy systems models. In building energy models for example, contrasting statistical techniques (e.g. Bayesian or frequentist) can be used to calibrate uncertain input parameters (Carstens et al., 2018). For this reason a number of more formal or systematic attempts have made to link qualitative storylines with quantitative energy systems models, in particular through an approach known as 'story-and-simulation' (Alcamo, 2008; Trutnevyte et al., 2014). Alternative qualitative narratives are first developed in story-and-simulation (SAS), from which exogenous parameters are derived for input into quantitative energy systems models in order to generate insights beyond the capabilities of qualitative or quantitative approaches alone (Wiebe et al., 2018).

Another prominent example of combining quantitative and qualitative tools, used widely by climate change researchers, is the integration of Representative Concentration Pathways (RCPs) and associated climate model projections, the Shared Socioeconomic Pathways (SSPs) and Shared climate Policy Assumptions (SPAs) (O'Neill et al., 2014). According to O'Neill et al. (2014, p.389), the overall objective of this process "is to produce integrated scenarios that will … include socio-economic and environmental conditions as affected by both climate change and climate policy." IAMs have been used to quantify emissions associated with the SSPs which present alternative, qualitative pathways of socio-economic development (Bauer et al., 2017; Schweizer and O'Neill, 2014). A limited number of standardised narrative scenarios (there are five SSP narratives) are promoted for shared use, which is consistent with computational and human constraints necessitating the use of small scenario sets (O'Neill et al., 2014; Wiebe et al., 2018). For each SSP, a marker scenario has been developed based on the outputs of one IAM selected to best represent the SSP's socio-economic narrative (Bauer et al., 2017). However, the common use of a limited number of narrative scenarios carries the consequence that a whole range of potential extreme outcomes or discontinuous futures may not be considered. One way to overcome this drawback could involve the use of large scenario sets, as have been developed for applications in defence and engineering (Wiebe et al., 2018).

A study by Trutnevyte (2016) indicates that SAS may help to account for societal and political changes that result in deviations from cost-optimal scenarios generated by energy systems models. SAS can also overcome a drawback with qualitative exploratory scenarios which allow the freedom to 'explore' discontinuous futures but may lack basic plausibility where they are unconstrained by technical, engineering or cost limitations, or by normative goals (e.g. climate change mitigation targets). Geels et al. (2016) propose several approaches for 'bridging' insights from IAMs and qualitative narratives emerging from socio-technical transitions theory, noting that these separate approaches are difficult to integrate, due to philosophical and methodological incompatibilities. Such bridging approaches could involve 'techno-economic checks of qualitative narratives outcomes' or 'socio-political feasibility checks of model outcomes', leading to revision of the original narratives or IAMs (through selection of more feasible low-carbon pathways) (Geels et al., 2016). This could help to increase understanding of levels of social and political disruption implied by different least-cost, climate mitigation pathways developed through IAMs.

Socio-technical transitions theory is utilised by van Sluisveld et al. (2018) to generate qualitative storylines about the strategies of different actors relating to low carbon technological innovations. These narratives can be 'translated' to create quantitative scenarios for inclusion in IAMs. However, there are various challenges with translating detailed information from transition narratives to IAMs. Existing IAMs mainly focus on technologies which have already been extensively and explicitly modelled (e.g. centralised, large-scale power generation technologies), with the result that compatible transition narratives will tend to include established rather than novel, disruptive innovations (e.g. social niche or demand-side innovations) (van Sluisveld et al., 2018).

Limited attempts have been made in the literature reviewed to explicitly translate disruptions developed through qualitative scenarios into quantitative energy models. One exception is a pilot project led by BEIS (2018), which assessed the impact of 'structural break' discontinuities from qualitative foresight scenarios on projections of energy demand and greenhouse gas emissions generated by BEIS's econometric Energy Demand Model. Anable et al. (2012) integrate qualitative storylines of lifestyle and behavioural change with quantitative modelling of transport energy use and demand.

3.3. Summary

Tables 3 and 4 summarise key insights from the literature discussed above on how the range of scenario and modelling tools vary by their relative strengths and weaknesses in representing purposive (co-ordinated or policy-led) and emergent (surprising or unanticipated) forms of disruption in energy systems. The assessment in this section suggests that the most well-suited methods for the assessment of discontinuity are

Table 3
Identified modelling methods and capability to capture disruption and discontinuity in energy systems: overview of strengths and weaknesses.

Energy systems / energy-economy model type	Strengths	Weaknesses
Optimisation and partial equilibrium models	Myopic / partial foresight optimisation models have been developed in order to capture emergent disruptions over shorter time horizons, e.g. technological breakthroughs.	Perfect foresight optimisation models assume optimal, long-term policy implementation and tend not to account for unpredictable social and political discontinuities.
Computable general equilibrium (CGE) models	CGE models can be used to analyse the impacts of energy and climate policies across multiple markets.	CGE models are typically rigid in attaining economic equilibrium around one base year. CGE models also have a low level of technological detail and are difficult to shock with rapid technological or social disruptions.
Simulation and agent-based models	Agent-based models simulate the interaction and adaptive behaviour of multiple agents operating under myopic foresight; agents can be disrupted by events that they cannot foresee.	Simulation and agent-based models may be less suited to understanding technological disruption. They have a low level of technological detail compared to technology rich, energy systems optimisation models.
Integrated assessment models (IAMs)	IAMs can be linked to insights from qualitative narrative scenarios or socio-technical transitions theory in order to understand levels of social and political disruption implied by cost-optimal climate mitigation pathways.	Given their global scale and coarse resolution, IAMs incorporate a simplified characterisation of global vs regional technological innovation and learning, and of geographically dispersed intermittent renewables or end-use energy technologies.

Table 4
Identified scenario methods and capability to capture disruption and discontinuity in energy systems: overview of strengths and weaknesses.

Energy scenario type	Strengths	Weaknesses
Exploratory (possible) scenarios	Multiple techniques are available to explore both emergent and purposive disruptions, including methods developed from corporate strategic foresight, exploratory external and exploratory strategic scenarios.	Qualitative exploratory scenarios may be unconstrained by technical, engineering or cost limitations, or by normative goals (e.g. climate change mitigation targets).
Normative (target-setting) scenarios	Normative transforming scenarios can assess the need for societal and political change in order to meet climate change targets.	Normative preserving scenarios generated using IAMs and cost optimal pathways to climate stabilisation do not directly assess emergent socio-economic discontinuities.
Predictive (probable) and what-if scenarios	Predictive what-if scenarios can compare alternative developments following on from a policy-led or emergent discontinuity.	Predictive forecasts which extrapolate historic trends are not well suited to analysis of potential emergent and unanticipated disruptions.

exploratory scenarios which assess policies and strategies in relation to possible future events and agent-based models in which multiple interacting agents cannot foresee discontinuities. The following section presents the evidence on modelling and scenario studies which explicitly set out to capture disruption or discontinuity.

4. How have disruption and discontinuity been represented in energy models and scenarios?

The second part of the evidence review identified 30 studies in a wide variety of international contexts (e.g. Australia, Canada, Mexico, New Zealand, Rwanda, USA, as well as Europe) which explicitly apply modelling or scenario approaches to the understanding of discontinuous change (Table A.4; Appendix C). Across these 30 studies, a variety of modelling / scenario methodologies have been used to investigate different types of disruption (Fig. 5). Each of the studies has been categorised according to: (1) the modelling or scenario method used and (2) emergent (uncoordinated) types of disruption and purposive (co-ordinated) forms of disruption captured by the modelling / scenario approach. Appendix D shows how methods used to represent disruption and discontinuity in the identified studies are distributed by year of publication and the location of the first author.

4.1. Representation of disruption and discontinuity and modelling / scenario approaches used

Fig. 4 shows types of disruption and discontinuity which were self-identified and modelled or captured in scenarios across the reviewed studies. The figure reflects that each study represented at least one and sometimes several types of disruption or discontinuity. In general, emergent disruptions have been captured more extensively across the models or scenarios used than purposive, co-ordinated disruptions. The most frequent types of emergent disruption featured in the documents reviewed are disruptive technological innovations and security of energy supply including from geopolitical disruptions. Climate change mitigation or adaptation policy is the most commonly captured purposive disruption.

Eight of the 30 modelling or scenario studies investigated emergent disruptions relating to the interaction between behavioural or lifestyle changes and the uptake of low carbon and smart technologies (Fig. 4). A similar number of studies incorporated the impact of wars, terrorist attacks, financial or economic crises into their scenario planning. Seven documents considered the impact of disruptive climate change, environmental crises or natural disasters. In terms of co-ordinated disruption, a more active role for society (specifically, societal transformation through a peer-to-peer society), environmental activism or collective responsible consumption and production, featured in seven documents.

The most common methods used across the 30 studies (Fig. 5) are firstly, qualitative participatory scenarios, including foresight techniques which are designed specifically to improve organisational and policy decisions by preparing for the consequences of future discontinuities (see section 3.2.5). Foresight scenarios help to identify weak signals of sudden, surprising events with dramatic impacts known as wild cards or black swans, and longer-term, interconnecting trends leading to more gradual and profound discontinuities (Heinonen et al., 2017a, 2017b; Mendonça et al., 2004, 2009). Secondly, in terms of quantitative modelling, agent-based or simulation models have been more frequently applied to the explicit study of disruptive or discontinuous change than optimisation or equilibrium models (Fig. 5). As noted in section 3.2.4, one possible reason for this is that unlike optimisation models, agent-based models enable the adaptive behaviour of multiple agents to be simulated in response to emergent disruptions and under conditions of myopic foresight.

4.2. Representation of disruption and discontinuity by sectoral categories

In this section, we consider the 30 identified modelling or scenario studies and discuss them in relation to different sectors or domains in which disruption or discontinuity takes place, including the energy system and technological change, geopolitical change and energy security, economic and market change, and social and lifestyle change.

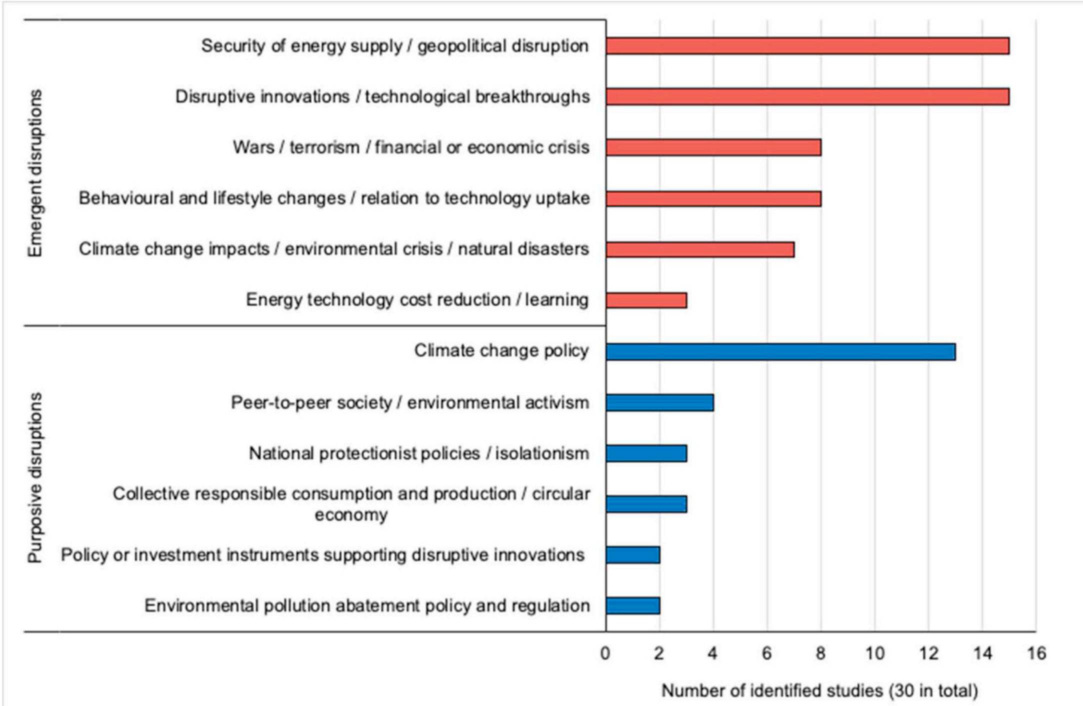

Fig. 4. Emergent and purposive types of disruption and discontinuity explicitly modelled or captured in scenarios in the identified studies (minimum 2 studies per category).

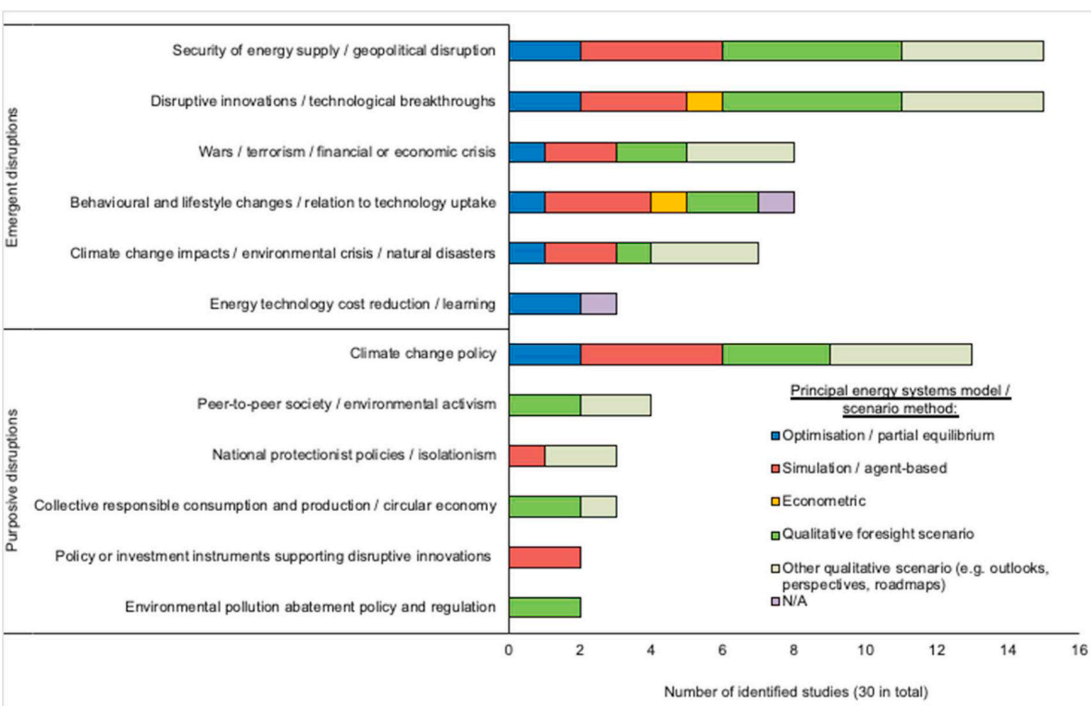

Fig. 5. Types of disruption and discontinuity explicitly modelled or captured in scenarios in the identified studies, and principal methods used (minimum 2 studies per category).

These sectoral categories have been devised as a means of grouping similar disruptions and discontinuities identified across the reviewed studies. We recognise that the categories are not mutually exclusive and there may be crossover between them.

4.2.1. *Energy system and technological change*

A number of observations can be made with respect to explicit representations of disruption and discontinuity in the studies reviewed, as they relate to energy system and technological change. Firstly, several agent-based modelling or simulation studies have been applied to understanding the resilience of energy supply infrastructure and its capacity to recover in response to short-term, emergent shocks such as flooding (Ehlen and Scholand, 2005; Kyriakidis et al., 2018; Varga and Harris, 2015). Chaudry et al. (2009) employ an alternative model methodology to examine similar short-term disruptions to infrastructure, by soft-linking three linear optimisation/cost-minimising models to examine the resilience of the UK energy system to shocks involving the loss of gas supply facilities. Secondly, Lof and Layzell (2018) use the Canadian Energy Systems Simulator (CanESS) model to develop transformation pathways which harness the convergence of disruptive technologies including autonomous and electric vehicles, ICT and AI, and policies which can accelerate the uptake of these innovations and help to meet Canada's 2050 climate change targets (Layzell and Beaumier, 2018; Lof and Layzell, 2018). This is framed in purposive language, in terms of directing disruption: "For policy makers to direct disruptive innovations to achieve societal objectives, it is important for them to have a vision for one or more Pathways for systems change" (Lof and Layzell, 2018). Thirdly, some perspective-based studies identified in the grey literature are concerned with discontinuities affecting incumbent energy industries, specifically the oil and gas sector (CSIRO, 2017; Hunter et al., 2016). The discontinuities incorporated in these perspectives may be more emergent, such as industrial transformation through digital technologies (CSIRO, 2017), or more purposive, such as the implications of a low carbon transition and how the incumbent sector could respond (Hunter et al., 2016).

4.2.2. Geopolitical change and energy security

Over half of the identified studies pertaining to geopolitical change and energy security use predominantly or wholly qualitative scenario or foresight approaches (Fig. 5). A cluster of studies with a range of qualitative methodologies, including wild card management systems (Mendonça et al., 2004, 2009), stress testing (Heiligtag et al., 2017) and environmental scenario planning (REMA, 2009), characterise various emergent, short-term disruptions. These disruptions include oil price shocks, earthquakes, terrorism and violent conflicts (Mendonça et al., 2004; 2009; REMA, 2009), and cyberattacks on interconnected, autonomous electric vehicles and the wider power distribution network (Heiligtag et al., 2017). A quantitative, partial equilibrium Global Gas Model is used by Richter and Holz (2015) to generate different scenarios of disruption in Russian gas exports to Europe, with the purpose of identifying where European gas supplies and infrastructure might be expanded and diversified.

Two separate scenario studies capture more purposive, geopolitical discontinuities arising from isolationism or national protectionist policies, as countries for example place greater priority on protecting indigenous resources and self-sufficiency (REMA, 2009; Transpower, 2018). Elsewhere, Heinonen et al. (2017a, 2017b) and Glenn et al. (2008) develop qualitative, participatory scenarios which feature longer-term, emergent discontinuities relating to failed states or more specifically the declining influence of the West in global politics in comparison to the rising influence of China and developing countries.

4.2.3. Economic and market change

Nine of the 30 studies reviewed explore disruption and discontinuity in relation to economic and market change. Financial crisis features in several of the documents, in particular qualitative scenarios (e.g. Mendonça et al., 2004; 2009; REMA, 2009; Transpower, 2018).

Agent-based models in the identified studies have been used to understand the economic impact of short-term, emergent disruptions and interdependencies between infrastructure and economic sectors (Ehlen and Scholand, 2005), and also to examine resource supply disruptions through economic collapse and recovery scenarios (Sherwood et al., 2017). Lamperti et al. (2018) employ an agent-based integrated assessment model ('Dystopian Schumpeter meeting Keynes (DSK) model') which is run based on Representative Concentration Pathway 8.5 (a high carbon, business as usual scenario), and simulates climate shocks and damages to economic performance (e.g. capital stocks and labour productivity) over the period 2000 to 2100 (Lamperti et al., 2018).

Heiligtag et al. (2017) use stress tests to explore alternative energy retail market disruptions such as radical price transparency or energy offered to customers for free in exchange for personal data. More fundamental changes to the structure of corporations to drive beneficial contributions to society, and interlinkages with a peer-to-peer society, are incorporated within the qualitative scenarios developed by Heinonen et al. (2017a, 2017b).

4.2.4. Social and lifestyle change

Social and lifestyle change are represented in qualitative scenarios which self-identify disruption and relate to more purposive (co-ordinated) change. Other studies use simulation/agent-based models to study the impact of emergent behavioural or lifestyle changes on technology uptake (Fig. 5), or to capture societal preferences or consumer behaviour (Shell, 2008, 2011; Wood, 2014). In section 3.2.3, we have noted that Grubler et al. (2018) use an IAM to develop a low energy demand, climate change stabilisation scenario involving rapid social and institutional change in the provision and consumption of energy services, although the authors do not expressly describe this as a disruption or discontinuity.

The CSIRO (2017) roadmap considers protests against the oil and gas sector organised through social media, and implications for obtaining licences to operate in the sector, while the global energy scenarios developed by Glenn et al. (2008) include the impact of environmental movements. Heinonen's Neo-Carbon Energy Societal Scenarios emphasise longer term, purposive discontinuities such as a more proactive role for society (e.g. a peer-to-peer society) and a cultural shift towards ecological values and lifestyles becoming the norm (Heinonen et al., 2017a, 2017b). In the 'Great Transitions' scenario of the Rwanda Environment Management Authority (REMA, 2009), environmental crises lead to the promotion of 'collective responsible production and consumption'.

4.3. Summary

In Table 5, we group examples of purposive and emergent discontinuities by the four sectoral categories discussed above. This analysis carries the limitation that only studies which refer explicitly to key words relating to disruption and discontinuity are included, as discussed in section 2 and set out in Table A.4 (Appendix C).

5. Conclusions and policy implications

In this paper we present an analysis of 30 studies, drawn from a wider systematic review, which self-identify and represent disruption or discontinuity in energy models and/or scenarios. A key limitation of our study is that we do not assess the extent to which disruption or discontinuity may also be represented implicitly or unintentionally in energy models and scenarios. Therefore, we cannot make claims about the overall extent to which these tools capture disruption or discontinuity in the literature. The extent to which certain categories of disruption, such as technological learning or renewables intermittency, feature in models or scenarios is likely to be underestimated in our analysis. Scenarios may also be viewed as disruptive from the perspective of other scholars. For example, McCollum et al. (2020) describe the Intergovernmental Panel on Climate Change (IPCC) 1.5°C pathways and Shared Socioeconomic Pathways (SSPs) as being based on disruptive drivers or sharp deviations in trends.

Across the documents analysed in our review, a variety of modelling / scenario methodologies have been used in studies which self-identify and investigate different types of disruption, most frequently relating to: disruptive technological innovations; geopolitical disruptions affecting security of energy supply; and climate change mitigation or

Table 5
Examples of purposive and emergent disruptions by sectoral categories across the 30 identified studies.

Category	Purposive disruptions/ discontinuities	Emergent disruptions/ discontinuities
Energy system and technological change	Climate change mitigation policy (impacts of policy or delays to implementation) (Gils, 2018; Shell, 2008, 2011) Policy, regulation or investment instruments supporting disruptive innovations aimed at societal goals, including climate change mitigation (Layzell and Beaumier, 2018) Environmental pollution from aircraft emissions and associated policy response (Mendonça et al., 2009) Significant cost reduction and technology learning of 'available' and 'unicorn' technologies (Heuberger et al., 2018)	Flood disruption to natural gas network (Kyriakidis et al., 2018) Shocks caused by loss of gas supply infrastructure (Chaudry et al., 2009) Disruptions to infrastructure systems, their interdependencies and resilience/adaptive capability (Ehlen and Scholand, 2005; Varga and Harris, 2015) Converging technological innovations, e.g. electric and autonomous vehicles, ICT and artificial intelligence (Heinonen et al., 2017a; Layzell and Beaumier, 2018)
Geopolitical change and energy security	Oil and commodity price shocks from climate change mitigation policies (Shell, 2008, 2011) National protectionist policies/isolationism (REMA, 2009; Shell, 2008, 2011; Transpower, 2018) Russia and export disruption to European gas supplies (Richter and Holz, 2015)	Cyberattack on interconnected energy and transport infrastructure (Heiligtag et al., 2017) Oil price shock; energy crises; earthquakes; terrorism; armed conflict (Mendonça et al., 2004, 2009) Erosion of national states and cultures; declining significance of the West in global politics and increasing influence of China and developing countries (Heinonen et al., 2017a, 2017b) Failed states (Glenn et al., 2008) Global nuclear war (Mendonça et al., 2004)
Economic and market change	Transforming large companies to drive positive societal change (Heinonen et al., 2017a) Innovation in business models enhances consumer demand for retrofitting buildings and housing (BEIS, 2018) 'Energy for free' offered by companies such as Amazon in exchange for personal data (Heiligtag et al., 2017) Radical price transparency – automatic energy supplier switching enabled by price comparison services (Heiligtag et al., 2017)	Impact of infrastructure disruptions on different economic sectors, based on interdependencies between economic firms and infrastructures (Ehlen and Scholand, 2005) Financial crisis (Gils, 2018; Mendonça et al, 2004, 2009; Transpower, 2018) Climate change 'shocks' impacting on economic performance, e.g. labour productivity and capital stocks and firm energy efficiency (Lamperti et al., 2018) Interruption to/collapse of supply chains, e.g. those associated with electric vehicles (Transpower, 2018)
Social and lifestyle change	Strong opposition to oil and gas sector from social groups organised through social media (CSIRO, 2017) Environmental movements (Glenn et al., 2008) 'Collective responsible production and consumption' promoted in response to environmental crises (REMA, 2009) Peer-to-peer society; ecological values and lifestyles as the norm (Heinonen et al., 2017b)	Smart grid, smart homes, internet of things/change in consumer behaviour (BEIS, 2018; Gils, 2018) 'A shift in consumer values away from material consumption' in response to economic crisis and volatility (Shell, 2008, 2011) Household life-stage changes and adoption of energy efficiency measures (Wood, 2014) Structural break related to societal preferences for low-carbon buildings and infrastructure (BEIS, 2018)

adaptation policy. The most common methods used to investigate discontinuities in energy systems are qualitative, exploratory scenarios, including foresight techniques which seek to identify wild cards, black swans, or weak signals of potential emergent disruptions. In terms of quantitative modelling, agent-based or simulation models have been more frequently applied to the explicit study of disruptive change than energy systems optimisation models. Likely reasons for this, which relate to respective capabilities and limitations of the different modelling methods, are summarised in the paragraphs which follow. Conversely, in our review of common types of energy systems models (stage 1), optimisation models are identified as one of the most prevalent categories.

Conventional optimisation and integrated assessment models have been used extensively to develop policy-led transformation scenarios of climate change mitigation (Gambhir et al., 2019a; Pfenninger et al., 2014). These models can help policy makers understand how to achieve long-term decarbonisation targets. They meet these targets by choosing combinations of low carbon energy technologies whilst minimising a quantitative value, such as total cost. They include a single decision maker that has perfect foresight about future trends in costs and prices. The results from these models can suggest rapid disruptive changes in energy systems, business models and user practices. They tend not to account for wider social and political changes which may disrupt the progress of decarbonisation. However, they can be modified to capture some disruptive events by running them in 'myopic' mode which limits the information available to the model about the future.

Li and Pye (2018) highlight the importance that decision makers place on the uncertainties around socio-political drivers of change, but the relatively low capability of energy systems models to account for these drivers. We have discussed several techniques for managing uncertainties in energy systems optimisation models, relating to poor knowledge about input parameters or equations governing model structure. One way to cover a greater range of uncertain, discontinuous outcomes is through the development of multiple near optimal scenarios, in addition to a single cost optimal scenario. This could allow for the design of climate mitigation policies which are more 'robust' to multiple, uncertain future developments (Trutnevyte, 2016; Gambhir et al., 2019b).

Agent-based models offer the potential to overcome some deficiencies compared to perfect foresight and single decision-maker models in representing disruptive change. Stochastic, agent-based models permit heterogenous interactions between actors to be simulated under conditions of bounded rationality and myopic decision-making in complex systems. This means that policies cannot be implemented perfectly at a global level in the absence of perfect cooperation or coordination amongst actors (Shchiptsova et al., 2016).

Our review has not identified agent-based models explicitly addressing discontinuities or disruption in relation to climate change mitigation policy. One reason for this may be that agent-based models have a low level of technological detail which may limit their practical application as tools for understanding how to decarbonise the energy system. Energy systems optimisation models can represent technological change in greater detail than CGE or agent-based models. There could be value in additional research into how agent-based models could be better adapted (or linked to technology rich models) for the purpose of understanding purposive disruption required for climate change mitigation policy.

The evidence review has highlighted a range of qualitative, exploratory scenarios which explicitly set out to explore discontinuous futures in low carbon energy transformation or in other sectors, e.g. by incorporating radical societal, market and geopolitical changes. These studies draw upon variants of scenario planning methods, including corporate foresight approaches, wild card management systems, and stress tests. However, these qualitative exploratory scenarios may not incorporate technical, engineering or cost constraints into their assessment of discontinuous and disruptive energy transitions.

Similar to Li and Pye (2018) on the assessment of uncertainty, our evidence review suggests that policy makers could improve their capacity to plan for disruption and discontinuity in energy systems through greater use of hybrid (i.e. qualitative scenario / quantitative energy systems model) approaches or by considering a wider portfolio of forward-looking techniques. The details of how such a multi-methods approach could work remains at an early stage of research investigation and implementation in energy and climate policy. Normative preserving scenarios of cost-optimal climate change mitigation are frequently developed using IAMs, and may imply profound changes to politics and society as a result of significant decarbonisation. Policy makers could use these together with backcasting scenarios, to assess which societal and political changes might be needed to meet climate change targets implied by cost-optimal (or near optimal) modelling scenarios.

Determining how to incorporate or combine the insights and techniques from qualitative scenarios with quantitative modelling is a key area for further research (Trutnevyte et al., 2014). Formal approaches for combining insights from energy systems models and scenarios, such as story and simulation, can help in principle to perform techno-economic checks on discontinuous qualitative narratives, or assess quantitative model outputs in the light of potential social and political disruptions. There are however continuing challenges with translating information from qualitative narratives to input parameters for quantitative energy systems models.

Continuing research is required to build on existing techniques which modify the structure, function and range of scenarios generated using optimisation models and IAMs in order to enhance their capability to account for uncertain, discontinuous outcomes. However, as the review in this paper has shown, energy systems optimisation models and IAMs are limited in their capability to anticipate discontinuities relating to social, economic, geopolitical and governance changes. Energy modellers could be more creative in embracing unlikely or non-mainstream assumptions in scenario development and would benefit from proactively seeking and integrating multidisciplinary insights that include social and political sciences as well as engineering and economics (Li and Pye, 2018; McCollum et al., 2020). Policy makers could better prepare for social, economic and political dimensions of disruptive change in energy systems by deriving insights from a broader range of expertise, scenario and modelling methods. These methods should include exploratory, foresight scenarios, simulation and agent-based models as well as repurposed energy systems optimisation models.

CRediT authorship contribution statement

Richard Hanna: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Robert Gross:** Funding acquisition, Conceptualization, Supervision, Methodology, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research presented in this paper was undertaken as part of the programme of the UK Energy Research Centre, which is funded by the UK Research Councils (award EP/L024756/1).

We thank the following for their input and comments, as part of the Expert Group: P. Taylor (University of Leeds); W. McDowall (University College London); J. McElroy (Wallington Consulting Ltd); M. King and A. Mortimer (Scottish Government); and J. Watson (UK Energy Research Centre / University College London).

Appendix A. Systematic review search terms and review protocol

For the first two stages of the systematic review, search terms were combined into a set of search strings and applied to Google Scholar (which draws upon a wide range of journal paper databases such as Science Direct, Taylor & Francis, Wiley Online and IEEE Explore) and Google, to capture grey literature from public, not-for-profit and corporate organisations. The search terms used in the Stages 1 and 2 reviews are shown in Tables A.1 and A.2 respectively. The search strings used and the total number of hits returned from each string were recorded. Where a particular search string returned a large number of hits, only the first 200–250 results were examined in order of the most relevant (as automatically generated by the search engine), considering the total number of search strings used and time constraints.

Returned results were filtered manually for relevance based on their title and abstract. If this was not sufficient to determine relevance, further inspection of the main text was performed, in order to focus attention only on those documents which were most directly useful in addressing the research questions.

As part of a standard protocol implemented by the Technology and Policy Assessment theme of the UK Energy Research Centre (Speirs et al., 2015), each document was assigned a relevance rating from 1 to 4, according to the following criteria:

(1) Article shows clear discussion and/or data that is directly focussed on some or all of the research questions.
(2) Article shows clear discussion and/or data that is related to but is not directly focussed on any of the research questions.
(3) Article mentions at least one of the search terms, but is of only limited relevance to the research questions.
(4) Article is found to be irrelevant or duplicate on closer inspection.

Table A.1
Search terms for Stage 1 review of reviews on energy system models and scenarios

Broad category	Tool	Review/meta-analysis terms
energy	model	review
	"energy systems model"	"systematic review"
	"energy systems analysis"	"evidence review"
	"integrated assessment model"	systematic
	"energy-economy model"	evidence
	scenario	meta-analysis
	"energy scenario"	compare
	projection	evaluate
	futures	analyse
	"transition pathway"	assess
		explore
		appraise

Table A.2
Search terms for Stage 2 review of disruption in energy systems models and scenarios

Energy model tools	Scenario tools	Discontinuity/disruption
"energy systems model"	energy	disruption
"energy systems analysis"	scenario	discontinuity
"integrated assessment model"	projection	shock
"energy-economy model"	futures	crisis
optimisation	"transition pathway"	transformation
equilibrium	outlook	surprise
simulation	roadmap	"wild card"
"agent-based model"	"vision statement"	"black swan"
	foresight	"weak signal"
	backcasting	megatrends
	what if	radical
	predictive	resilience
	exploratory/explorative	
	normative	

Appendix B. Expert Group membership

The Expert Group consisted of the following members:
Peter Taylor (University of Leeds);
Will McDowall (University College London);
John McElroy (Wallington Consulting Ltd);
Michael King/Andrew Mortimer (Scottish Government);
Jim Watson (UK Energy Research Centre/University College London).

Appendix C. Literature identified through the systematic review

Table A.3
Identified reviews / meta-analyses of energy systems model and scenario typologies (Stage 1 review)

Citation	Database/source	Type of study/document/article	Review of energy systems models?	Review of scenarios?
Trutnevyte et al. (2016)	Google scholar	Journal article		Yes
Hughes et al. (2009)	Google scholar	Journal article		Yes
McDowall et al. (2014)	Google scholar	Journal article	Yes	Yes
Koppelaar et al. (2016)	Google scholar	Journal article		Yes
Paltsev (2016)	Google scholar	Journal article	Yes	Yes
Amer et al. (2013)	Google scholar	Journal article		Yes
Kowalski et al. (2009)	Google scholar	Journal article		Yes
Wilkinson et al. (2013)	Google scholar	Journal article		Yes
Tourki et al. (2013)	Google scholar	Journal article		Yes
Kishita et al. (2016)	Google scholar	Journal article		Yes
Keirstead et al. (2012)	Google scholar	Journal article	Yes	
Zeng et al. (2011)	Google scholar	Journal article	Yes	
Pfenninger et al. (2014)	Google scholar	Journal article	Yes	
Hall and Buckley (2016)	Google scholar	Journal article	Yes	
Strachan et al. (2011)	Google scholar	Journal article	Yes	
Després et al. (2015)	Google scholar	Journal article	Yes	
Kahouli-Brahmi (2008)	Google scholar	Journal article	Yes	
Keirstead and Shah (2013)	Google scholar	Journal article	Yes	
Gargiulo and Gallachóir (2013)	Google scholar	Journal article	Yes	
Gorenstein Dedecca and Hakvoort (2016)	Google scholar	Journal article	Yes	

(continued on next page)

Table A.3 (*continued*)

Citation	Database/source	Type of study/document/article	Review of energy systems models?	Review of scenarios?
Amann et al. (2009)	Google scholar	Journal article	Yes	
Strachan et al. (2011)	Google scholar	Journal article	Yes	
Koppelaar et al. (2016)	Google scholar	Journal article	Yes	
Schmid et al. (2012)	Google scholar	Journal article	Yes	
Karali et al. (2012)	Google scholar	Journal article	Yes	
Densing et al. (2016)	Google scholar	Journal article	Yes	
Pye and Bataille (2016)	Google scholar	Journal article	Yes	
Connolly et al. (2010)	Google scholar	Journal article	Yes	
Giannakidis et al. (2015)	Google	Grey literature	Yes	
Layzell and Beaumier (2018)	Google	Grey literature	Yes	
DeCarolis (2014)	Google	Grey literature	Yes	
Klein (2017)	Google	Grey literature	Yes	
Benson (2016)	Google	Grey literature	Yes	
Anandarajah et al. (2009)	Google	Grey literature	Yes	
Karjalainen et al. (2014)	Google	Grey literature	Yes	Yes
Benichou and Mayr (2014)	Google	Grey literature	Yes	Yes
NREL (2017)	Google	Grey literature	Yes	No
Cao et al. (2016)	Google	Grey literature	Yes	Yes
Martinot et al. (2007)	Google	Grey literature	Yes	Yes
World Energy Council (2013)	Google	Grey literature		Yes
Blomgren et al. (2011)	Google	Grey literature		Yes
Deilmann and Bathe (2009)	Google	Grey literature		Yes
van Notten et al. (2005)	Extracted from Stage 2 review	Journal article		Yes
Linstone (2011)	Extracted from Stage 2 review	Journal article		Yes
Heinonen et al. (2017b)	Extracted from Stage 2 review	Grey literature		Yes

Table A.4
Energy systems modelling or scenario studies identified through the evidence review which explicitly represent disruption or discontinuity (Stage 2 review)

Citation	Database/source	Type of study/document/article	Country/ies of authors' institution[1]	Scenario/modelling sector	Words/phrases used to diagnose explicit representation of disruption in model(s)/scenario(s)
Bauer et al. (2003)	Google scholar	Journal article	Mexico	Energy	"shock"
Richter and Holz (2015)	Google scholar	Journal article	Germany	Energy	"disruption", "shock"
Venayagamoorthy and Mitra (2011)	Google scholar	Journal article	USA	Energy	"shock"
Schirrmeister and Warnke (2013)	Google scholar	Journal article	Germany	Innovation	"weak signal"
Mendonça et al. (2004)	Google scholar	Journal article	Portugal/Finland/Germany	Corporate/organisational planning	"wild cards", "weak signal", "surprising and potentially damaging events", "crises", "disruptive"
Mendonça et al. (2009)	Google scholar	Journal article	Portugal/Germany/Finland	Civil aviation and investment banking	"wild cards", "disruptive", "discontinuities", "weak signals", "crises", "surprises"
Hunter et al. (2016)	Google	Grey literature	UK/Netherlands	Oil and gas sector	"megatrends", "disruption", "disruptive"
Heinonen et al. (2017a)	Google	Journal article	Finland/Germany	Energy	"crises", "surprise", "wild cards", "black swans", "weak signals", "discontinuities"
Glenn et al. (2008)	Google	Grey literature	US	Energy	"conflicts", "turmoil", "backlash", "disrupt"
Heinonen et al. (2017b)	Google	Grey literature	Finland	Energy	"weak signals", "ecological collapse", "ecological crisis", "megatrends", "black swans"
Accenture (2014)	Google	Grey literature	Global	Energy	"disruption", "disruptive energy technologies"
Heiligtag et al. (2017)	Google	Grey literature	Germany	Energy	"shocks", "disruptions", "extreme scenarios", "crisis"
REMA (2009)	Google	Grey literature	Rwanda	Environmental	"disasters", "conflicts", "crises", "climatic shocks"
Navigant (2018)	Google	Grey literature	Netherlands	Energy	"disruptive", "disruptive decarbonisation scenario"
CSIRO (2017)	Google	Grey literature	Australia	Oil and gas	"megatrends", "disrupted", "rapid technological change"
Transpower (2018)	Google	Grey literature	New Zealand	Energy	"rapid change", "disruptive", "disrupting", "surprises", "conflict"
Layzell and Beaumier (2018)	Google	Grey literature	Canada	Energy/climate change policy	"disruptive", "rapid change"
Lof and Layzell (2018)	Google	Grey literature	Canada	Energy/transport	"disruptive", "disruptive innovations", "disruption"
Wood (2014)	Google	Masters thesis	UK	Energy	"shocks", "sudden or extreme changes in life-stage"
Kyriakidis et al. (2018)	Google	Journal article	Singapore/Switzerland	Energy	"disruption", "shock", "resilience"
Chaudry et al. (2009)	Google	Grey literature	UK	Energy	"resilience", "shocks"
Ehlen and Scholand (2005)	Google	Grey literature	US	Energy-economy	"disruptions", "crisis"
Varga and Harris (2015)	Google	Grey literature	UK	Infrastructure systems	"disruption", "resilience"
Lamperti et al. (2018)	Google	Journal article	Italy/France	Energy-economy/climate change policy	"shocks", "crises"

(continued on next page)

Table A.4 (*continued*)

Citation	Database/source	Type of study/ document/article	Country/ies of authors' institution[1]	Scenario/modelling sector	Words/phrases used to diagnose explicit representation of disruption in model(s)/ scenario(s)
Sherwood et al. (2017)	Google	Journal article	US	Economy/natural capital	"disruptive", "shock", "economic collapse"
Heuberger et al. (2018)	Expert-recommended	Journal article	UK	Energy	"disruptive events", "disruptive technology innovation", "disruptive technological change", "unicorn technology"
Gils (2018)	Expert-recommended	Grey literature	Germany	Energy	"disruptive elements", "disruption"
BEIS (2018)	Expert-recommended	Grey literature	UK	Energy	"structural breaks"
Shell (2011)	Snowballed from source identified in Stage 1 review	Grey literature	The Netherlands	Energy	"crisis","financial crisis", "financial crash","economic slump", "shocks", "discontinuities"
Garard et al. (2018)	Expert-recommended	Grey literature	International	Energy	"wildcards", "disruptions", "megatrends", "nuclear disasters"

[1] If author has more than one affiliation, then the primary affiliation is taken.

Appendix D. Principal methods used to represent disruption and discontinuity in identified studies (Stage 2 review), distributed by year of publication and location of first author

Table A.5 shows that 18 out of the 30 identified studies in the Stage 2 review were published in the latest four year period (2015–2018). Qualitative scenario studies covered a greater range of publication years (5 from 2003 to 2014, 7 from 2015 to 2018) compared to quantitative modelling studies. Of the latter, all 11 simulation or agent-based modelling studies were published from 2011 to 2018, with 6 of these published in the most recent four years.

The location of the first author varies across methodologies used in the 30 documents (Table A.6). For example, all 4 optimisation and partial equilibrium modelling studies were published by authors in Europe. Simulation or agent-based models were used by authors publishing their work in a wider range of locations internationally: Europe, the US, Canada and Singapore. Most studies using qualitative, exploratory foresight scenarios were published by authors located in Europe.

Table A.5
Principal methods used to represent disruption or discontinuity and year of publication

Year of study publication	Optimisation and partial equilibrium models	Simulation and agent-based models	Accounting models	Econometric models	Qualitative Foresight scenarios	Other qualitative scenarios (e.g. outlooks, perspectives, roadmaps)
2003			1			
2004					1	
2005						
2006						
2007						
2008						1
2009	1				1	1
2010						
2011		2				
2012		1				
2013					1	
2014		2				
2015	1	1				
2016						1
2017		1			2	2
2018	2	4	1	1	2	
Four year totals	**Optimisation and partial equilibrium models**	**Simulation and agent-based models**	**Accounting models**	**Econometric models**	**Qualitative Foresight scenarios**	**Other qualitative scenarios (e.g. outlooks, perspectives, roadmaps)**
2003–2006	0	0	1	0	1	0
2007–2010	1	0	0	0	1	2
2011–2014	0	5	0	0	1	0
2015–2018	3	6	1	1	4	3

Table A.6
Principal methods used to represent disruption or discontinuity and first author location

Region	Optimisation and partial equilibrium models	Simulation and agent-based models	Accounting models	Econometric models	Qualitative Foresight scenarios	Other qualitative scenarios (e.g. outlooks, perspectives, roadmaps)
Europe	Germany	Italy		UK	Finland	Germany
	Germany	Netherlands			Finland	UK
	UK	UK			Germany	
	UK	UK			Portugal	
					Portugal	
					UK	
North America		Canada	Canada			USA

(*continued on next page*)

Table A.6 (*continued*)

Region	Optimisation and partial equilibrium models	Simulation and agent-based models	Accounting models	Econometric models	Qualitative Foresight scenarios	Other qualitative scenarios (e.g. outlooks, perspectives, roadmaps)
		Canada	Mexico			
		USA				
		USA				
		USA				
		USA				
International other		Singapore			International	Australia
						Rwanda
Regional totals	**Optimisation and partial equilibrium models**	**Simulation and agent-based models**	**Accounting models**	**Econometric models**	**Qualitative Foresight scenarios**	**Other qualitative scenarios (e.g. outlooks, perspectives, roadmaps)**
Europe	4	4	0	1	6	2
North America	0	6	2	0	0	1
International other	0	1	0	0	1	2

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