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Renewable and Sustainable Energy Reviews

A systematic review of energy systems: The role of policymaking in sustainable transitions

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ABSTRACT

The language of systems can be highly useful when defined clearly. It can help make sense of the interconnectedness of key actors, the 'emergence' of outcomes from large numbers of interactions, and the proposed transformation – by many governments - towards sustainable energy systems. However, 'whole systems analysis' and 'systems thinking' is often too vague to guide this project well. To explore these issues in depth, we show how they arise frequently in UK energy policy research and its impact on policymaking. First, our systematic review shows how researchers present patchy or inconsistent stories, in which the role of policy and policymaking is unclear, when they describe energy systems. Second, UK and devolved governments often use the language of systems to propose paradigmatic energy policy change, but refer to a metaphor rather than academic insights. Third, we outline three ways to make clearer sense of energy transitions and policy with reference to *socio-technical*, *complex*, and *social-ecological* systems.

1. Introduction

The language of systems and 'whole systems thinking' could make a profound contribution to scientific and policy analysis. It appears useful when defined clearly enough to make sense of complex processes and interactions – such as between technological innovation and policymaking – by highlighting the interconnectedness of key actors and the 'emergence' of outcomes from large numbers of exchanges. It is a distraction when defined so vaguely that it means everything and nothing: people use the language of complexity too loosely, and recommend systems thinking without clarifying how it works in practice. A focus on interconnectedness could range from the consideration of a long but relatively simple supply chain in which we can predict the impact of innovations, to identifying the key elements of a complex system that produce non-linear outcomes outside of anyone's control. Therefore, we could *think* we are describing the same thing, and making conceptual and empirical progress, but actually be talking at cross-purposes, contributing to conceptual sludge, and making no meaningful impact on 'systems thinking' in policy and practice.

These issues are central to energy policy research for four key reasons. First, the changing language of systems reflects a change of thinking in disciplines such as engineering and policy studies. Pre- and post-war approaches described systems in relation to the scientific and rational means to transform a sense of 'chaos' into manageable and well-defined problems, and to symbolize great human achievements in 'large technical systems' such as electrical power systems. In contrast, modern references to complex systems describe a 'human-built world' that is beyond the comprehension of single disciplines and requires continuous interdisciplinary cooperation [[1,2[1,2,p.1,3,p78]]. Crucially, the incorporation of society - and social and political science – into this discussion makes a difference to the reference points we find in systems analysis, such as the 'deterministic' systems often found in physical sciences, or systems as 'social constructions' in social science [4]. Rather than producing a common and widely-held understanding, interdisciplinary discussion has produced many 'phases' of conceptualisation without removing the sense that energy systems 'puzzle researchers and "confound engineers, social scientists, historians, economists, policy planners, and political leaders"' [[5,p.1067]]. As a result, two conflicting references to energy systems still co-exist, to think of systems as complicated but under our control *and* as complex and out of our control.

Second, these challenges notwithstanding, energy policy scholars see interdisciplinary 'whole systems research' as an important way to tackle 'complex societal challenges such as sustainable energy' [[6,p.74]] and to understand transitions to low carbon energy systems [7,8]. This effort can take three complementary forms: widespread scholarly convergence around one interdisciplinary approach such as the Multi-Level

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Abbreviations	
ETIS or TIS	energy technology innovation system
GHG	greenhouse gas
IPSA	International Political Science Abstracts
IAD	Institutional Analysis and Development
MLP	Multi-Level Perspective
STT	socio-technical transitions
UKERC	UK Energy Research Centre

Perspective (MLP) [7]; attempts to incorporate key disciplines, such as political science, into a wider framework to address under-theorised aspects of systems [9]; and major initiatives to fund and manage interdisciplinary work, such as the UK Energy Research Centre (UKERC) [6]. In each case, there are two important and connected aims: to better understand and incorporate the role of politics and policymaking in whole systems research; and, to use this understanding to have a more meaningful impact on policy and practice, largely to facilitate the sustainable energy transition being studied [6].

Third, however, compared to many other policy areas, energy-related behaviour and outcomes appear more likely to 'emerge' from non-governmental action or defy central government attempts to control them [10]. Indeed, the impact of politics or government action does not always feature strongly in energy system analysis. In studies of sectors such as health and education, the focus is often on outcomes that emerge from systems despite central government efforts to control them [10]. In energy systems studies, it is more common for models to focus primarily on private sector and consumer behaviour, or describe socio-technical systems in which innovation plays a much clearer role than politics. Further, governments themselves often describe an unwillingness or inability to manage energy supply and demand - using a systems metaphor to provide a sense of realism about their likely influence – in a way that would not be politically feasible in other policy areas [33].

Fourth, in this context, the potential value of systems thinking is clear, but its impact on policy and practice is not. Energy systems research brings together academics from many disciplines (including engineering, social, political and policy sciences, and interdisciplinary fields like transport studies) with practitioners from many sectors (including public, private, and third sectors, and quasi-governmental bodies such as regulators) but does not give them a clear language to communicate. Most discussions of systems rely on implicit understandings or vague references to a metaphor. Analysts *often* rely on the same UKERC definition: 'the set of technologies, physical infrastructure, institutions, policies and practices located in and associated with the UK which enable energy services to be delivered to UK consumers' [11,p.iv]. There is also *some* reference to an established way to conceptualise systems, such as with reference to the MLP [12]. However, there is insufficient attention to the sum total of intellectual activity, at least in relation to comparable initiatives such as to address socio-ecological systems [13,9:pp.177-8]).

Overall, it is difficult to tell if systems thinking describes a metaphor or actual system with specific properties, what type of system exists, the key factors that would cause change from a high to low carbon system, and therefore what systems thinking could mean beyond the vague sense that many things are connected and energy system change is complicated. Therefore, more clarity is vital to high quality policy-relevant analysis of energy system change.

To that end, our team was funded via UKERC to analyse the relationship between energy systems and complex policymaking systems in the UK, focusing on multi-level policymaking (resulting from EU, UK, and Scottish Government policy) and the potential impact of Brexit on the energy system (a task which necessitates clarity on the meaning of energy system) [60,61]. Our role was to highlight the value of political

science and policy studies, to clarify the role of policy and policymaking in energy systems, and encourage a greater role for systems thinking in policymaking.

To do so, we perform three essential tasks. First, we provide a systematic review of the relevant literature to identify how researchers conceptualise the role of politics and policymaking in energy systems. Second, we focus on UK government strategies, and the Scottish Government's [14] energy strategy as an exemplar of systems thinking, to identify how they operationalise the language and insights provided by energy systems research. Is this research making an impact, or do policymakers merely adopt a metaphorical language? Third, we identify the key energy systems studies – and complementary approaches in the wider policy studies literature – that help us make systematic reference to systems thinking and encourage policy impact. We describe three approaches and their take-home messages:

- *Socio-technical transitions.* Identify the conditions under which innovation helps transform energy systems.
- *Complexity theory.* Identify how to respond when the future is uncertain and major policy change is not under central government control.
- *Social-ecological systems.* Identify the conditions under which actors can cooperate to manage resources and reduce environmental damage.

The choice of approach matters to the way we communicate, understand energy systems, and seek to act on that basis. Therefore, we focus primarily on a conceptual review to identify the meaning that researchers and policymakers give to energy systems when they seek to understand them and encourage their transformation.

2. A systematic review of energy systems research

We conducted our review in three stages to identify how researchers conceptualise (a) energy systems *and* (b) the role of policy and policymaking in their transformation. This combination of requirements is highly restrictive, since it requires researchers to give a full account of their theoretical understanding (in other words, we exclude articles that simply refer to established approaches in their bibliographies). Although we appear to privilege policymaking in the search, we actually examine if researchers *discuss it at all* (and if they use political science insights to do so).

First, we searched six databases between September and November 2018 including: Web of Science (all databases), International Political Science Abstracts (IPSA), Scopus, International Bibliography of the Social Sciences, Science Direct, and UKERC. We combined the search term 'energy system(s)' with policy related search terms – 'policy', 'policies', 'policy maker(s)', 'policymaker(s)', 'policy system(s)', and 'policy cycle (s)' - in the articles' title, abstract, and key words. Second, we applied a set of inclusion/exclusion criteria: (1) the outputs should be peer-reviewed journal or UKERC publications; (2) the search term(s) should be present more than once in the body text; and (3) they should be accessible in English. We did not exclude papers based on geographical coverage, date of publication, or period covered, even though our analysis is tailored to the UK context. Third, we used 'snowballing' to increase the sample when one article clearly relied on another to make a key part of its argument. Munro and Cairney agreed the search terms. Munro conducted stages 2 and 3. Munro and Cairney agreed on the inclusion of the core papers we discuss below (including the snowballed papers) (see Table 1)

This review is largely *conceptual*: we analyse the extent to which each paper makes a non-trivial reference to energy systems and policy. Many comparable *empirical* reviews can assume that similar methods are used in each paper, and are replicable by different research teams. They can accumulate data by combining the results of multiple studies, such as in the systematic review of experimental methods (in fields such as health).

Table 1
Number of papers resulting from each of the literature review searches and sifting processes.

	Web of Science – All Databases	IPSA: International Political Science Abstracts	Scopus	International Bibliography of the Social Sciences	Science Direct	UKERC	*Total*
Date of search	24 Sept. 2018	26 Sept. 2018	25 Sept. 2018	24 Sept. 2018	18 Oct. 2018	14 Nov. 2018	Sept. to Nov. 2018
Stage 1 Initial number of results	230	9	498	139	154	85	1115
Excluded	158	8	435	124	137	69	931
Duplicate	2	0	37	0	2	0	41
No access	8	1	9	1	0	0	19
Included after Stage 2 Sift	**62**	**0**	**17**	**14**	**15**	**16**	**124**
					Snowballed papers		**10**
					Stage 3 Top Papers		**24**

As Annex A shows, in our review, the papers do not provide such a common reference point for the accumulation of data. Nor is there an agreed method or common framework to design and conduct research. Consequently, our review is necessarily thematic, to identify the concepts and issues raised most frequently and in most depth, and to incorporate the results into a narrative of the main approaches (compare with [15]).

Our approach is *potentially* subject to more judgement, regarding the extent to which a published study reaches a certain threshold for inclusion, than simple quantitative reviews with exclusion criterion relating to methods and results. However, to answer the question "does this study present a non-trivial discussion of the phrase 'energy system'?" actually required minimal discretion. Of the 124 most relevant papers, almost all either (a) described an energy system without defining key terms or operationalising them, or (b) analysed aspects of systems and referred to other work to define them fully. Therefore, a smaller set of papers could be included for *reference*, because they used a proxy definition by inviting the reader to read a different paper to understand the meaning of energy system. Finally, a very small set of papers engaged directly with the term 'energy system', or identified a specific approach, to the extent that we could identify clearly how it related to the conceptual or empirical discussion of policymaking.

We identified only 14 that provided a dedicated discussion of energy systems, and their connection to politics and policymaking, with reference to the development of a well-formed approach (such as the MLP) or insights from the political and policy sciences. We use them as *exemplars of key approaches*, to provide a relatively in-depth and qualitative discussion of each approach. We also used snowballing to increase the sample when an article relied on another to make part of its case. All of these articles focused to some extent on the idea of transitions towards a radically different – unsustainable to sustainable, high to low carbon, and/or fossil fuel to renewable - energy system. As such, many are also covered in the reviews of transitions studies that identify similar problems with clarity and focus [9:pp.175-6]. Many refer to the literature on 'socio-technical transitions' (STT) or 'sustainability transitions' [16, p.97]. In some cases, their exposition of STT terms compensate for a lack of definition of the elements of an energy system: to focus on STT dynamics is to try to explain how an energy system moves to sustainability. In many other cases, there is brief reference to STT or energy systems without sufficient clarity. Or, studies make superficial reference to policy scientists (such as Peter Hall or Elinor Ostrom) or concepts (such as institutions or complex systems) without showing sufficient engagement with the terms to connect their own purposes to a wider academic project. We supplement these studies by identifying the ways in which they *could* connect to more coherent approaches in relation to complex and social-ecological systems.

3. Whole systems thinking in government

We performed a more limited review of UK and Scottish government documents to identify *exemplar cases* of strategies that take 'whole

systems' research and/or thinking seriously. Our aim was to identify a subset of documents in which the authors provided a clear definition of energy system and the role of government and policy in it. If so, it would allow us to identify a promising translation from whole systems research into policy and practice.

This translation is crucial to current plans for major policy change. The UK Government has made several commitments in relation to climate change and reducing greenhouse gas (GHG) emissions that require significant shifts in the UK's energy system. The UK Climate Change Act (2008) presents a legally binding target of GHG emission-reduction levels of 34% by 2020 and 80% by 2050, followed by an announcement in 2019 of an amended 'net zero' target (100% reduction) (1990 baseline levels). This Act was a 'major shift' for the UK [17]. It positioned the UK as the first country to have a legally binding framework to cut carbon emissions. The UK has strategies to deliver on these commitments, with energy as a key component.

However, while there is *some* reference to energy systems in UK government documents, 'systems thinking' is not a key feature. There is an almost exclusive tendency – similar to most papers in our review – to use terms such as 'energy system' frequently rather than precisely. For example, the UK Renewable Energy Strategy 2009 [18] outlines how the legally binding target, to ensure 15% of energy is sourced from renewable sources, is to be reached by 2020. This target is to apply across the whole energy system, although the boundaries of the system are not defined. There is vagueness in the use of the concept of transition to refer to changes in the system in relation to renewable energy, a low-carbon future, a low-carbon economy, and in terms of transition planning and costs. The National Renewable Energy Action Plan [19] does not employ the concept of transition as it outlines the pathway to meet the 2020 renewable energy targets which the UK was obliged as a member country of the European Union to submit to the European Commission (under EU Directive 2009/28/EC). Although the notion of energy system is *mentioned*, it is in vague reference to important elements of the future energy system.

In contrast, the Scottish Government's [14,p.5] energy strategy provides more explicit reference to systems thinking and the 'whole system view', and its approach is lauded by participants in the energy sector (which we interviewed as part of our wider research project). It identifies functional *requirements* of a system such as *resilience* [14,p.2], described by Chaudry et al. [11,p.4-5] as 'the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances'. In particular, resilience requires, 'lower levels of imports and hence energy demand; diversity of supply; and robust physical infrastructure' [14, p.5]. In that context, and bearing in mind its limited policy responsibilities, the Scottish Government [14,p.6-8], describes 'the connections between the energy system and all parts of the economy', to seek, for example, 'a well-balanced system capable of providing secure and affordable energy to meet Scotland's needs' [14,p.6-8].

However, it does not (a) define an energy system, (b) model specific elements of systems (*the document's images are very loose metaphors*), or (c) refer to wider conceptions of systems in the energy literature. It describes many different things as systems - including: 'integrated local energy systems', 'smarter domestic energy applications and systems' and 'heat, transport and electricity systems' - and describes a distinctive Scottish energy system as 'part of the wider Great Britain and European energy market' and subject to 'disruptions in the international energy system' [14,p.6-12].

Consequently, from our reading of the strategy, and discussions with civil servants (interviews, December 2017), the language of systems *projects a very general way of thinking holistically* about energy policy, rather than with specific reference to socio-technical systems or well-formed approaches. We would describe its most useful metaphor as akin to a telescope, to zoom out and analyse the interconnectedness of key processes. This strategy marks a change from previous approaches. Previously, there was more focus on self-contained initiatives such as increasing renewables. Now, the Scottish Government considers the overall effect of a collection of policy instruments over which it has:

- High and often direct influence (including key aspects of the supply mix, such as renewables, shale oil and gas, and nuclear, and investment for energy efficiency).
- Minimal or informal influence (such as the electricity market, and North Sea oil and gas).

Such accounts show some progress towards incorporating academic systems research into strategy. They are potentially useful, since policymaking systems resemble complex systems, and governments could describe a pragmatic and legitimate role to encourage a well-functioning rather than a centrally controlled system. Yet, without any attempt to define a system, its key components and processes, and the specific role of government in helping to secure specific targets, these discussions remain vague metaphors with potential to mislead rather than inform (compare with the similarly eclectic language in Ref. [54]).

More clarity is required to help academics and policymakers connect their work to existing scholarship *and* produce more coherent 'whole systems' inspired policymaking analysis. Further, since interdisciplinary cooperation has produced multiple ways to understand and engage with energy systems, we need to establish what people mean when they refer to an energy system. To that end, we outline the three main ways in which academics turn general systems thinking into practical understandings. We describe them as stories to help us identify not only their descriptions of the nature of systems but also the take home messages (morals) for actors seeking to influence energy system transition.

4. Three stories of energy systems and system transformation

In this section, we use key articles as exemplars, to show how some studies engage in a relatively precise and systematic way to operationalise 'energy system' (and show how their work relates to the larger field). Like Rogge et al. [21], we show that these approaches provide different storylines. They tell a different story about the nature of an energy system, its key dynamics and actors, and the key factors on which to focus when researching and seeking to produce – with the aid of policy and policymaking - an energy system transition. We have not found any study that engages with the connections between all three. We therefore describe the limited ways in which researchers have made connections across concepts, or between analytical and policymaking aims, and fill in the blanks with reference to more general studies of policy and policymaking (see Ref. [22]). Our aim is to aid clear comparison rather than synthesise insights in a single framework [compare with 9].

4.1. Innovation in socio-technical systems: the Multi-Level Perspective and technological innovation systems

Story: high carbon energy regimes are highly path dependant, but innovation within an initially insulated niche – supported by a wider social and political environment - can aid 'socio-technical transitions' (STT) or 'sustainability transitions' to a low carbon system.

The 'Multi-Level Perspective' (MLP) - developed by Geels [23,24] and colleagues to help explain socio-technical system dynamics with reference to innovation - clearly has traction in the study of energy systems. However, engagement ranges from little more than reference to a concept before providing a citation, to using MLP for broad inspiration (or mild criticism [53,p.333]), more meaningful critical engagement [25], and clear attempts to summarise and make sense of the key elements of the three levels ('*niche innovations*, *socio-technical regimes* and *macro-landscape pressures*'), such as in this example:

'The landscape represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society and only change slowly. The socio-technical regime reflects the prevailing set of routines or practices used by actors, which create and reinforce a particular technological system. In contrast, the existing regime is thought of as generating incremental innovation, whilst radical innovations are generated in niches. The latter are spaces that are at least partially insulated from normal market selection in the regime. Niches provide places for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user–producer relationships' [26,p.442] (see also [25,p.96]).

Some articles provide substantive discussion of a specific field, but remain vague on how their recommendations relate to system dynamics. For example, Mitchell and Woodman [27,p.2644] do not define energy system but rely on STT language to help describe a proposed shift in the UK from a 'regulatory state paradigm' to 'public value regulation'. The transition would be aided by changes to markets (to give economic incentives to suppliers of renewables and energy efficiency technology, and choice to customers), networks of demand and supply, and regulation. For example, the UK Government's current approach does not foster 'the necessary trust' in government and regulators to achieve climate change goals, or sufficient incentives for the 'innovation required for a move towards a sustainable energy system' [27,p.2645]. There is too much faith in the market to produce sustainable choices, the regulatory process encourages industry to 'game' economic incentives for short-term reward, and too few stakeholders in long-term energy sustainability have a meaningful role in political and economic choice [27,p.2646-8].

Other articles refer to STT and other concepts before signalling their own conceptual analysis. For example, De Boer et al. [28,p.490] focus on the general STT concept and argue that energy systems are part of a wider 'energy landscape' consisting of the physical world and human culture. They describe *six systems, each with four scales* (local, regional, national, global) [28,p.491]. Although everything is connected in practice, *analytically* the energy system is confined to 'extracting, transporting, storing, generating, transmitting, distributing and using energy from different resources' and is separate from:

- economic ('trade, finance')
- bio-physical ('land use, ecology, morphology, water, natural resources')
- physical infrastructure ('built environment, transport, infrastructure')
- community ('identity, culture, acceptance'), and
- governance ('public institutions, laws, rules, norms) systems [28, p. 490].

Rhodes et al. [29, p. 5602] describe a global energy system with reference to Gallagher et al.'s [30] concept of an 'energy technology innovation system' (ETIS, or TIS). TIS analysis uses the language we

might associate with complexity theory (below) – by emphasising the non-linear nature of systems - but to develop a global level exploration of the role of technology innovation and R&D within wider systems containing many public and private actors. Such work has major policy-making implications, regarding the idea that governments may seek to invest heavily in sustainable and renewable technologies, but are unable to 'pick winners' in a system characterised by:

- uncertainty about which innovations will be successful [29,p.5620] and
- the importance of phases, including a 'formative' phase of experimentation when actors seek a market and political foothold, and a 'market expansion' phase in which the technology has enough economies of scale to reduce the need for public subsidy [25,p.99].

The most direct engagement – and clearest use of MLP - comes from articles in which Geels is a co-author. Rogge et al. [21, p. 1] apply it 'to develop socio-technical storylines that show how low-carbon transitions can be implemented'. The storylines serve to:

1. Compare future aims - such as to meet the 2° C global climate change target via reforms to electricity production - with current practices, to identify key 'bottlenecks' and how to overcome them 'through social interactions, learning processes and coalitions'.
2. Connect these solutions to public deliberation on issues such as the 'the centralized and decentralized nature of the future energy system'.
3. Identify specific policymaking practices and 'policy mixes' that could support sustainable transitions [21, p. 1] (see also [31]).

This approach helps engage with the implementation gaps - major differences between policy intentions and actual outcomes - that feature strongly in accounts of proposed energy transitions. It combines a focus on the technical feasibility of energy system change (largely via quantitative models) with the political feasibility of policy change. The idea is to generate widespread public and policymaker ownership of major policy change by producing scenarios ('pathways') and encouraging public deliberation on the costs and benefits of particular ways to move to energy sustainability. There remains a focus on 'niches', supporting innovations in technology, within this context of supportive policy mixes and public support. A new regime requires the 'destruction' of the old - by, for example, reforming the electricity market and reducing subsidies on the use of fossil fuels – which involves challenging powerful 'vested interests' [21,p.3]. It requires a 'different policy culture' in which many actors deliberate and experiment with new technologies and rules and help change how other actors understand the policy problem. It requires 'changes in institutional arrangements and governance structures' to support this shift. They provide two ideal-type scenarios in which to analyse this process:

1. 'Technological substitution'. Key actors are 'incumbent' in industry and politics, substituting some energy technologies for others, in a largely unchanged market.
2. 'Broader regime transformation'. Key actors are 'new firms, social movements, civil society actors' producing 'fundamentally new ways' to use energy via new technology, markets, and consumer behaviour [21,p.3].

On that basis, they show differences in, for example, ways to change the energy supply mix - by design or unintended consequence - and the rapid versus incremental shift of approach [21,p.7].

These conceptual developments help address two problems identified in the STT literature. *First, there is not enough discussion of politics and policymaking within STT analysis.* Technical models focus on a *functional analysis of what is required* from an energy system rather than the key actors, rules, and processes that get us there. Yet, it is a truism in policy

studies that policy outputs and outcomes relate weakly to such requirements [33]. Indeed, the function of political systems is to provide ways to debate these requirements and highlight policy priorities. Without this political analysis, it is difficult to know how researchers – or governments - would tell a useful story to connect a policy vision with actors and choices key to its delivery. Therefore, Rogge et al. [21, p. 3] and Geels et al. [12, p. 2–3] seek to go 'beyond the techno-economic variables that dominate model-based scenarios' to help identify the:

- actors that would be central to social and political change,
- 'political feasibility' of major policy change among key policy-makers, and
- 'social acceptance' of major change in energy supply and use.

Similarly, Kuzemko et al. [16, p. 96–99] propose a 'new, interdisciplinary framework for the analysis of governing for sustainable energy system change' inspired by STT accounts but incorporating (to some extent) 'new institutionalist' analyses to understand how policymaking systems and rules help produce a shift from minor to major policy change.

This focus is clearer in Markard et al.'s [32] analysis because it brings in expertise on policy studies - via Ingold - to identify the conditions under which policy changes to support transition towards more renewable energy supply and less energy demand. During transitions, 'new products, services, business models, organizations, regulations, norms and user practices emerge' but the process can take many decades [32, p. 217]. They focus on a key policy theory - the 'advocacy coalition framework' - which suggests that people enter politics to turn certain beliefs into policy, form coalitions with people who share their beliefs, and compete with other coalitions. This competition extends to the exercise of power to define energy as a policy problem (for example, is fossil fuel use primarily an *economic good* or *environmental bad*?). Long-term resistance to change can come from path dependence and the fixed beliefs of the actors who are central to socio-technical systems *and* part of a dominant advocacy coalition [32, p. 220].

It is rare for major policy change to result from dominant actors simply changing their 'core beliefs'. Rather, the ACF describes routine policy-oriented learning coupled with internal and external 'shocks', in which a previously dominant coalition changes in response to policy failure or events external to the subsystem (some actors leave, some modify their 'policy core' and 'secondary beliefs'), or another coalition exploits events to gain ground [32, p. 219]. For example, the latter create a niche and invest in new technologies, there is high demand for the new technology following an external event (such as nuclear or oil price crisis), and actors exploit this attention and demand to gain ground within the policy subsystem [32, p. 219]. This initial process helps change the direction of government policy, to boost support for wider changes to energy supply and demand. For example, in Switzerland, the 'pro-economy' coalition is larger and more powerful than 'pro-ecology', but events such as Fukushima have altered the former's beliefs about the relative benefits of different forms of energy supply, while the latter has demonstrated that renewable energy has major economic benefits [32, p. 232].

Second, there is not enough discussion of learning (a topic with a rich literature in policy studies [48]). As with ETIS analysis, Winskel et al. [25, p. 96] describe hopes for energy transition in 'technological innovation' within a field characterised by many different 'policy initiatives' to support many technologies, coupled with high uncertainty about which innovations will bear long term fruit. This problem complicates analysis of future scenarios:

- 'technology roadmaps' may underestimate the importance of wider socio-technical and political factors,
- 'energy system models' may underestimate the 'uncertainties, contingencies and non-linearities of system change' and present a too-broad account of the dynamics of innovation [25, p. 97], while

- ETIS and MLP [25, p. 97] provide detailed case studies but with limited crossover between highly abstract and highly detailed accounts.

These limitations prompt them to focus on *learning pathways* as the key to transitions [25, p. 97]. For example onshore wind 'evolved over decades of learning-by-experience and learning-by-research' while solar PV has a far greater emphasis on the latter, and nuclear involves more learning by internationally coordinated 'replication' [25, p. 102]. Learning helps reduce many possibilities to few - such as when market concentration and standardisation replaces a diverse range of models – either via incremental or radical steps [25, p. 103-4].

4.2. Complexity and complex systems theory

Story: governments may propose a transition from high to low carbon energy systems, but policy outcomes are not in their control and there is too much uncertainty to predict the effect of their actions. Many accounts emphasise the need for central governments to give more discretion to local actors to adapt to a rapidly changing environment.

Complexity theorists in social and political science describe *complex policymaking systems*: many actors in the public and private sector interacting with each other in different parts of a system, which are not subject to central government control [22,33]. Key elements of a complex system include:

- interdependence between many actors across (and outside) government
- positive and negative feedback (some actions are dampened, others amplified)
- 'sensitivity to initial conditions' and path dependence (initiated by historical choices with a cumulative effect)
- 'strange attractors' (extended regularities of behaviour despite the potential for major instability)
- The local 'emergence' of outcomes despite attempts at central government control [34,35].

Put another way, policymakers operate in environments in which there are many policymakers and influencers competing for power, across many venues with their own rules, networks, beliefs, and ways to interpret and respond to socioeconomic conditions and events [22]. They are subject to 'bounded rationality' (which includes the inability to process all relevant information), and can only pay attention to a small proportion of their responsibilities. In that context, policymakers struggle to understand far less control complex systems [22]. Further, the same governmental intervention can have a minimal or maximal effect, and a 'policy that was successful in one context may not have the same effect in another' [22, p. 349]. Events and decisions made in the past contribute to the formation of institutions that influence current practices, and the policymaking context resembles a 'fitness landscape' to which only some actors can respond effectively [36,37]. 'Multi-centric policymaking' is pervasive (energy policymaking is spread across many venues), no single central government can control policy, and policy makes an important but highly unclear contribution to policy outcomes [38].

Few energy systems articles describe complexity theory in this much depth, but several engage with this basic story of high uncertainty and low policymaker control, to challenge the idea that governments can set and deliver major energy transitions strategies. Butler et al. [39, p. 665] focus on the relationship between complex systems, government policy, and public opinion. They describe high uncertainty about how to achieve the 'strong policy imperatives to transition toward low carbon energy systems' to meet energy efficiency and security aims and climate change targets. Referring to the 'nature of complex systems', they identify 'no scientific means of establishing causality' when outcomes 'arise from fundamentally complex or arbitrary behaviour' [39, p. 666].

Therefore, we should avoid 'illusory, control-based approaches' [39, p. 667]. Their example is the 'public acceptability' of major changes to energy transitions – requiring UK public support for nuclear power, electric cars, and new forms of heating - that seem impossible to predict. However, we can identify how policymakers can 'frame' policy changes to *seek* public support, with reference to: efficiency/minimising waste, making sure the energy supply is secure, and encouraging fairness and affordability [39, p. 669; see also [56] on framing to reconcile transition and tourism/recreation aims].

Stafford and Wilson [40] analyse the implementation of policies by Regional Transmission Organizations (in the US and Canada) to encourage more use of renewable energy in power grids. They describe 'implementation systems' to note the indeterminacy of policy change in complex systems [40, p. 223]. They identify the need for highly context specific data on behavioural change, and use 'grounded theory' (induction and qualitative methods, allowing themes to emerge from documents and interviews) to understand the implementation of a specific policy instrument in a local context. They refer to the political and economic authority of key actors - as well as the norms, practices, beliefs, and values influencing action - to show that implementation issues extend beyond the idea that policymakers with political authority can simply deliver major change according to a functional imperative [40, p. 227].

This in-depth analysis of one strategy compares with studies of the interaction between many policy instruments. First, Spyridaki and Flamos [41, p. 1091] examine studies of *policy mixes*, or the interacting effect of the many policy instruments that appear to be designed to address energy and climate change problems. The overall effect is 'non-linear' rather than cumulative. A game-changing shift in policy outcomes could come from: the interaction between many instruments; a major change in their *effectiveness* or *efficiency*; and/or a major shift in policy direction caused by a crisis (prompting a change of government or a government's replacement of the experts on which it relies). In other words, we need to examine the potential-versus-actual impacts of policy when:

(a) instruments tend to be 'characterized by high complexity levels' so that few are in a position to understand them fully
(b) they enter a wider political and economic environment in which policy change has intended and unintended consequences, and
(c) the details of policy change, negotiated by stakeholders, can have a minimal or maximal effect when dampened or amplified by a complex system [41, p. 1092].

Government policy has an impact, but it is difficult to measure, to the extent that the review of many different existing approaches to evaluation – 'need analysis, program theory evaluation, experiment and quasi-experiment, impact assessment, cost effectiveness analysis and cost to benefit analysis, multicriteria analysis, etc'- shows high uncertainty about cause and effect. Further, if we brought in more political science insights [33], we could add that the analysis of many policy tools or instruments should include their *political* as well as *technical* feasibility. The former relates, for example, to their distributive or redistributive effects, which prompts a response from the people most likely to be subject to their effects. Analysis of this aspect of feasibility has begun to appear in evaluations of energy transitions which focus on 'social equity, social costs and political acceptability' and include a focus on shifting employment, 'quality of life' and citizen empowerment during deliberations on major social and policy change [41, p. 1096-7].

Second, Cox et al. [42] explore the wider range of factors that may affect energy policy. Current evaluations of the 'policy mix' may be too restrictive if they focus only on instruments designed explicitly to influence energy supply and demand without considering the spillover effects of a wider mix. To present a more 'holistic' approach, Cox et al. [42, p. 3–4] identify *thirteen* non-energy sectors with a non-trivial impact on energy policy. They include environmental and

marine/land use (affecting transport and energy demand, and onshore/offshore wind), and public services like health and education (as major energy consumers). Cox et al. [42] also note four cross-sectoral factors: regulation and the market/state relationship; the scale at which policy is made, from local to international or in centralized/decentralized systems; the policy process at each scale; and, major events such as Brexit (see also [52: 569] on policy instruments to encourage behavioural change).

4.3. Social-ecological systems (and frameworks examining social and political cooperation)

Story: we need effective institutions to manage finite resources and minimise environmental damage. Key institutions are not – and need not necessarily be – controlled by governments or single central governments. Rather, we need rules and mechanisms to ensure high cooperation among many actors and societal ownership of the means to achieve energy transitions.

Studies of energy transition tend to include the requirement for high stakeholder and public ownership of policy change, particularly when they involve unpopular changes in the short term to manage long-term outcomes. However, most accounts provide superficial or incomplete attention to this issue, at least when compared to approaches such as the *Institutional Analysis and Development* (IAD) framework [13] discussed below. In most accounts, there is great emphasis on the need for more 'co-production' of research and policy between researchers and social and policy actors. However, this development is at an early stage compared to other disciplinary fields on which energy studies could draw to understand the relationship between (a) functional requirements of a natural or environmental system, and (b) the dynamics of social and political systems to help secure that end.

Two key articles focus on the need for much more contact between researchers and the actors – including policymakers and influencers across many levels of government – crucial to the delivery of energy transitions. Chilvers et al. [26, p. 440] - as part of the Transition Pathways Consortium - present a model from which most others could learn, in which they harness collaboration 'between engineers, social scientists and policy analysts' to try to make sense of 'whole systems' thinking in relation to 'transition pathways for a more electric, low-carbon energy system'. To that end, they draw on STT and MLP insights to identify a coherent research project, including:

- a clear aim (such as the UK Government 'net zero' commitment to reduce GHG emissions) connected to objectives including 'the simultaneous delivery of low carbon, secure and affordable energy services'
- three 'low-carbon, socio-technical transition pathways', connected to 'the feasibility, social acceptability, and environmental and economic impacts of the pathways [26, p. 440].

In turn, each pathway describes different factors key to transition:

1. *The market is the main pathway and form of governance.* In this scenario, the main technologies are coal and gas (combined with carbon capture), nuclear, and offshore wind; government management is minimal, focusing on strategy and carbon prices; and, heating/transport demand for electricity is 'much greater than today'.
2. *There is major central government coordination.* The main technologies remain the same, the government commissions low carbon electricity from big businesses, but more energy efficiency means demand is 'slightly higher than today'.
3. *There is major civil society direction.* The main technologies are solar, onshore and offshore wind, renewable heat/power sources; there is more community ownership and service user engagement to produce local solutions, and a combination of efficiency improvements and consumer awareness produces demand 'lower than today' (compare

with [52] on policy to encourage behavioural change to reduce demand, and [58,59] on the role of consumer and business feedback in 'smart energy system' design).

Yeh et al. [47, p. 169] take a comparable but less intensive approach. They outline *six* models that identify the requirements for key aspects of energy system transformation – including major improvements in building, transport, and industrial efficiency, more renewables, and reduced demand associated with activities such as car use - in the case study of California. While useful to prompt discussion, the models are limited because they make many assumptions of 'perfect markets, perfect competition, and zero transaction costs' to identify the potential economic benefits of key moves, such as in relation to capital investment and employment in new technologies (these markets may be better described as 'adaptive' [55]). Further, they do not provide clear policy recommendations regarding how these requirements can be met in real world political situations in which there are multiple policy aims to consider, such as to ensure some degree of equity in energy use and costs. The latter requires more cooperation between modellers and the actors, such as politicians, who need to (a) make sense of and act upon the scenarios, and (b) construct persuasive stories about the nature of energy systems and the likely causes and beneficiaries of required change.

Such articles do not engage fully with the implications of 'systems thinking' in which we seek a sustainable energy system in which (a) there can be no single central government controlling the agenda, and (b) many actors need to work together either voluntarily or without the full ability to coerce behaviour. *This latter point is **the** major challenge to energy system transitions, but it is tackled rarely in this literature.* Fortunately, other disciplines provide a wealth of insights on which to draw when engaging in energy systems thinking. Most importantly, the IAD provides a language to analyse crucial dynamics:

1. *Polycentric governance.* Polycentricity describes (a) 'many decision centres' with their own separate authority, (b) 'operating under an overarching set of rules', but with (c) a sense of 'spontaneous order' in which no single centre controls the rules or outcomes (see [43, p. 237, 254] and [44, p. 123]). *Polycentric governance* describes 'policymaking centres with overlapping authority; they often work together to make decisions, but may also engage in competition or conflict' [38, p.2]. The empirical aim is to identify the conditions under which polycentric governance arrangements, held together by a collection of mutually agreed rules, provide more efficient, equitable, democratic, or sustainable practices than a single central government [38].
2. *Governing the commons.* Ostrom [45] won the Nobel Prize in economics for her work on managing 'common pool resources' (CPRs). CPRs are collective resources – such as land, water, and some sources of fuel – with two properties: (a) it is difficult to exclude actors from enjoying their benefits, and (b) their use by one usually diminishes their value to another [49].
3. *Institutions.* Institutions are the 'rules, norms, and shared strategies that structure human behaviour and choices' [50: 310]. The crucial point is that they can be (a) formal, written, and widely understood, or (b) informal, unwritten, and difficult to detect. Therefore, when *designing* energy transitions we seek rules that are 'collectively created, adapted, monitored, and enforced' [50: 310]. However, we also need to anticipate the informal rules that 'exist in the minds of the participants and sometimes are shared as implicit knowledge rather than in an explicit and written form' [51: 23].
4. *Policy design.* Ostrom describes the 'design principles' present within hundreds of examples of successful communal arrangements. Put simply, they allow CPR users to trust each other and cooperate for the long-term because users: help design institutions, know their role within them, calculate their return to investment, resolve disputes

quickly and proportionately, and maintain accountability without external government interference [45: 90].

This work has wider implications to 'social-ecological systems' and energy systems, in which the aim is to identify the factors essential to some degree of self-organisation, when many actors seek to cooperate – in the absence of single central government control - to avert a catastrophic degradation of environmental resources. The broad aim is to encourage resource users to (a) value long-term sustainability for an entire population more than the short-term rewards to themselves, and (b) self-organise to secure this outcome [46]. Ostrom [46]'s key considerations include the role of leadership, norms, social capital, as well as:

- The size of the resource system to manage. If too large, the costs of establishing boundaries are too high. If too small, there are insufficient benefits to prompt collective action.
- 'Predictability of system dynamics' and knowledge of the system. Users will perceive the costs of self-organising to be lower if they understand the resource system and the likely effect of their actions.
- 'Number of users'. Large numbers of actors are difficult to manage, but may be needed to manage large resource systems.
- 'Importance of resource to users'. Users are more likely to self-organise if they depend on the resource units for their livelihood.
- 'Collective choice rules' Users are more likely to self-organise if they have high autonomy to create and monitor their own rules [46, p. 420-1] (described in Ref. [33, p. 124]).

However, the impact of such factors is always indicative because, 'As in most complex systems, the variables interact in a nonlinear fashion … Simple blueprint policies do not work' [46, p. 421]. The co-production of institutions is crucial because each context is different, and policy design is only successful when people work together to create the rules consistent with their wider 'culture' [57]. If so, these insights have profound implications for the ways in which actors would design and deliver pathways to energy system transition.

5. Conclusion

'Whole systems thinking' is crucial to understanding energy-related behaviours and their policy implications, and contributing to the transition from an unsustainable to sustainable energy system. However, our review of the published academic literature and exemplar government strategies suggests that people use this language without defining energy systems, identifying their key dynamics, or demonstrating the mechanisms for systemic transition. Policy and policymaking are important to that discussion, but it is generally unclear what the policy mix should be, and its likely effect. Non-governmental action is crucial, but the relationship between governmental and other actors is not clear. Without this clarity, we may all agree on a very general aim without knowing how to achieve it or talk about it sensibly.

Our systematic review identifies three relatively coherent ways in which analysts conceptualise energy systems. We *could* try to combine their insights to tell an overall story of energy system transitions. First, niche innovation, supported by a wider social and political environment, can help produce the transition to a low carbon system. Second, governments may be able to help facilitate this transition, but policy outcomes are not in their control and there is too much uncertainty to predict the effect of their actions. They need to share responsibility for outcomes with the local actors able to adapt to a rapidly changing environment. Third, much of this responsibility will lie with non-governmental actors who need to find ways (and incentives) to cooperate to manage resources and reduce environmental damage. We need to develop rules inside and outside government to produce (a) the mechanisms to ensure high cooperation among many actors, (b) and societal ownership of the means to achieve energy transitions.

However, at present, these perspectives provide more value when compared with each other, such as to highlight major dilemmas, including:

1. Models of socio-technical systems are still too focused on the functional requirements– rather than the actual dynamics – of policy-making systems. Models of complex policymaking systems often suggest that policymakers are not in the position to fulfil those requirements.
2. Models of complex systems and socio-ecological systems often seem to recommend a reduced- or non-governmental solution in which a wide range of actors come together to produce new rules and practices. However, they do not provide feasible solutions to policymakers in countries – such as the UK – where governments must demonstrate their competence by projecting the sense that they are in control (particularly in the era of Brexit as an alleged symbol of 'taking back control' – see Refs. [60,61]).

Further, there is value in rejecting the *prospect* of a common understanding of 'whole systems thinking', and perhaps even the current value of the phrase itself, since it suggests that there is a singular approach to which we can all contribute. In contrast, politics and policymaking is about *contestation* built largely on competing values and preferences, and current references to a vague phrase such as 'whole systems thinking' may help depoliticise these issues and give the misleading impression that research will solve political problems.

Acknowledgment

Annex A. The method and results of selected articles

Yr	Author	Region	Method or approach	Results
2002	Geels	UK	Empirical case study to illustrate the multi-level perspective.	The MLP helps understand technological transitions.
2004	Geels	n/a	Further develops the multi-level perspective for sociotechnical transitions.	Incorporates the 'user side' and makes an analytical distinction between sociotechnical systems, actors, and institutions/rules.
2010	Mitchell, Woodman	UK	Examines the UK and the regulatory state paradigm	The UK's regulations hinders efforts to reduce carbon dioxide emissions.
2012	Gallagher et al.	Global	A literature survey and a set of empirical case studies are examined.	The concept of an 'energy technology innovation can be used to inform policy design.
2013	Bridge et al.	UK	Seminar series (2009-11) based on empirically-grounded assessments (sectors, technologies, or regions), and research involvement in other research initiatives.	Six concepts (location, landscape, territoriality, spatial differentiation, scaling, and spatial embeddedness) help describe the geographic aspects of low carbon energy transitions.

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Yr	Author	Region	Method or approach	Results
2014	Spyridaki, Flamos	n/a	Literature review. Assessment framework focuses on different types of evaluation methods.	The field of energy and climate policy research analysis is still a young field with a range of quantitative and qualitative methods.
2014	Rhodes et al.	Global	Datasets were compiled on public and private research and development expenditure for energy from international organizations.	The diverging viewpoints on the global energy system's development has reinforced the relatively large amount of effort and innovation activity in the energy sector.
2014	Winskel et al.	Global	Expert consultation about energy supply technologies.	A 'learning pathways' matrix is presented to connect learning rates and the contextualisation of innovation studies.
2015	Butler et al.	UK	Energy system scenario and policy analysis with stakeholder interviews, in-depth deliberative workshops, and an online survey.	Public responses to energy system change can be better anticipated by engaging with a range of problem and solution framings.
2015	Chaudry et al.	UK	Literature review, workshop, and input-output model to assess carbon budget technology uptake estimates and assess of the impact of technology uncertainties.	The risks and uncertainties of the UK's heat system transition to low carbon include heat pump deployment, electricity grid decarbonisation, and heat network deployment.
2015	Duić et al.	n/a	Summary of articles in the Special Volume (Sustainable Development of energy, Water and Environmental Systems) of Journal of Cleaner Production.	The exchange of research results, new ideas, and practical experience is important to increasing public awareness of sustainable development and related issues.
2015	De Boer, Zuidema	Europe	Research reports were analysed, interviews and workshops conducted, and a set of four cases involved further interviews.	The 'energy transition' can be fostered through an area-based approach that can help to understand the factors that make innovative energy initiatives viable.
2016	Markard et al.	Switzerland	Codes the beliefs systems of actors and coalitions based on their written statements about a policy proposal in a survey.	The relationship between advocacy coalitions have remained stable in Switzerland since 2013, but support for an energy transition has increased.
2016	Yeh. et al.	United States	Compares six energy models.	Energy models could be more useful to policymakers if they emphasise consumer behaviours, heterogeneity of impacts, uncertainty, and spatial modelling.
2016	Stafford, Wilson,	United States	Case study, using strategic action field theory to analyse documents, participant observation, and semi-structured qualitative interviews.	Emphasises energy policy implementation. Recommends that stakeholders are able to make decisions that transform the energy system by shaping the use and value of energy technologies.
2016	Cox et al.	n/a	A literature review of key works, then a snowball approach to examine how energy systems are affected by a range of policies.	Cross-sectoral review which identifies under-researched themes including liberalisation, governance processes and structures, Brexit, devolution, centralisation and centralisation.
2016	Kuzemko et al.	UK Germany	Applies a theoretical framework to the illustrative example of governance in the UK and Germany.	Emphasises the value of an interdisciplinary framework to analyse sustainable energy systems, using sociotechnical transitions and new institutionalist concepts.
2017	Chilvers et al.	UK	Interviews, workshops with stakeholders, and analysis of historical analogies, to develop three low-carbon sociotechnical transition pathways.	Three low-carbon transition pathways are presented for the United Kingdom along with the challenges, insights, and opportunities for each.
2017	Shortall, Kharrazi	Iceland, Japan	Literature review combined with key informant interviews.	Culture influences the geothermal developments in Iceland and Japan, and each approach has advantages.
2017	Hall et al.	UK	In-depth interviews, analysed through coding and narrative analysis to extract key discourses and themes.	The 'adaptive market hypothesis' is useful to analyse the finance of energy systems (electricity market reform and renewable energy finance analysis in the UK).
2018	Axon et al.	EU	Literature review, sampling 50 energy related behaviour change initiatives from the UK, Ireland, France, Italy, and Spain. The 'Behaviour Change Wheel' model was applied to categorise the behaviour of the initiatives.	There are significant knowledge gaps between what is being applied in practice versus that is known to be effective to achieve behavioural change in relation to the energy system (with an over-reliance on education and awareness-raising projects).
2018	Rogge et al.	Germany	Develops sociotechnical scenarios, using a 'bridging' approach to model scenarios and identify 'transition bottlenecks' in Germany's electricity system.	A larger emphasis is needed on societal experimentation and proactive anticipatory deliberation processes for system transformation where technological substitution of components requires agency from incumbents.
2018	De Boer et al.	Netherlands	Empirical evidence from seven case studies to map artefact-actor networks.	Local initiatives can influence energy transitions. They tie systems and scales together as area-based niches.
2018	Smith et al.	United States	Case studies based on media content analysis, ethnographic participant observation, and stakeholder focus groups.	Describes the tangible and intangible social dynamics that are part of energy system transitions. Examines the social effects of wind farms on tourism, recreation, and quality of life.

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