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Energy and complexity: New ways forward

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HIGHLIGHTS

- Review application of complexity methods to energy systems and systems change.
- Attributes: self-organisation, path dependency, emergence, co-evolution, adaptation.
- Modelling approaches: agent-based models, dynamic network models.
- Long-term energy systems change: co-evolutionary framework.
- Policy challenges: systemic interactions, decision-making under uncertainty.

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ABSTRACT

The purpose of this paper is to review the application of complexity science methods in understanding energy systems and system change. The challenge of moving to sustainable energy systems which provide secure, affordable and low-carbon energy services requires the application of methods which recognise the complexity of energy systems in relation to social, technological, economic and environmental aspects. Energy systems consist of many actors, interacting through networks, leading to emergent properties and adaptive and learning processes. Insights on these type of phenomena have been investigated in other contexts by complex systems theory. However, these insights are only recently beginning to be applied to understanding energy systems and systems transitions.

The paper discusses the aspects of energy systems (in terms of technologies, ecosystems, users, institutions, business models) that lend themselves to the application of complexity science and its characteristics of emergence and coevolution. Complex-systems modelling differs from standard (e.g. economic) modelling and offers capabilities beyond those of conventional models, yet these methods are only beginning to realize anything like their full potential to address the most critical energy challenges. In particular there is significant potential for progress in understanding those challenges that reside at the interface of technology and behaviour. Some of the computational methods that are currently available are reviewed: agent-based and network modelling. The advantages and limitations of these modelling techniques are discussed.

Finally, the paper considers the emerging themes of transport, energy behaviour and physical infrastructure systems in recent research from complex-systems energy modelling. Although complexity science is not well understood by practitioners in the energy domain (and is often difficult to communicate), models can be used to aid decision-making at multiple levels e.g. national and local, and to aid understanding and allow decision making. The techniques and tools of complexity science, therefore, offer a powerful means of understanding the complex decision-making processes that are needed to realise a low-carbon energy system. We conclude with recommendations for future areas of research and application.

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Contents

1. Introduction

Current systems of energy provision and demand need to change significantly in order to address the so-called energy 'trilemma' – how to consistently provide affordable energy services, achieve security of energy supplies and reduce greenhouse gas emissions from energy conversions to mitigate climate change. This will require substantial deployment of low-carbon technologies and energy-efficiency measures, the costs and benefits of which are often highly uncertain. Moreover, energy systems consist of a range of actors – producers, generators, suppliers and end users who will frequently have conflicting objectives. These actors and technologies interact through physical and social networks governed by institutional and political structures, the development of which is also uncertain. Together, these features make energy systems examples of complex systems, the study of which has become a fruitful area of research and application over the last 30 years, particularly since the founding of the Santa Fe Institute in 1984. However, the concepts developed in the complexity domain are only just beginning to be applied to the understanding of energy systems. This paper aims to set out the ways in which complex systems thinking and modelling could be useful in understanding the complexity of energy systems and how these systems change, in order to address current and future policy challenges.

In the United Kingdom (UK), there are energy policies aimed at addressing all three aspects of the trilemma: the 2008 Climate Change Act sets a legally-binding target of reducing the UK's carbon emissions by 80% from 1990 levels by 2050 [1]; the Warm Homes and Energy Conservation Act [2] places a duty on government to make sure no person lives in fuel poverty by 2016; and there are several policy actions to support energy security in the UK [3]. Policy measures enacted to achieve these targets and objectives, such as Electricity Market Reform [4] and the Green Deal [5], lead to multiple interactions between changes in actors' behaviours and further technological and institutional changes, which may serve to help or hinderthe achievement of policy goals. However, analysis of policy measures and instruments tends to be dominated by techno-economic models that do not reflect the full complexity of energy systems, particularly in relation to systems interactions and actor behaviours. Hence, we argue that there would be great value in applying approaches and models that incorporate complex systems thinking by reflecting both interactions between actors, networks and institutions in energy systems that give rise to emergent system properties and the limited or 'bounded' rationality of those actors in relation to decision-making under uncertainty. Complexity science and its associated modelling methods enable the study of how interactions between different elements of a system give rise to the collective emergent behaviour of that system and how the system interacts and responds to its environment and evolves over time. In this paper, we review recent advances in complexity science and modelling, and examine the ways in which these would enable those working in the energy domain to better understand and model the complexity within energy systems for the purpose of advancing adoption of new technologies, policies and behaviours.

Some of the insights reported here are drawn from a workshop coordinated by the UK Energy Research Centre (UKERC) and held in the UK in July 2012 that drew together academics across multiple disciplines who were interested in complexity and energy modelling [6].

In Section 2 we outline the characteristics of complexity science and the energy system, and examine how complexity science offers an alternate approach to understanding energy system change. In Section 3 we discuss the purpose of computational modelling of complex systems and briefly summarise some of the modelling methods available. We also briefly highlight the realities of modelling complex systems including the data requirements and discuss the advantages that complexity modelling methodologies can bring to the energy domain over traditional modelling methods. In Section 4 we give examples of the application of complexity modelling reported in recent research work in the areas of transport, user behaviour and infrastructure. In Section 5 we discuss how complexity and coevolutionary ideas can be applied to understanding long-term energy systems change. We conclude in Section 6 with recommendations for areas of future work.