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Supply chains and energy security in a low carbon transition

This special edition to be published in Applied Energy brings together a range of papers that explore the complex, multi-dimensional and inter-related issues associated with the supply or value chains that make up energy systems and how a focus on them can bring new insights for energy security in a low carbon transition.

Dealing with the trilemma of maintaining energy security, reducing greenhouse gas emissions and maintaining affordability for economies and end users are key issues for all countries, but there are synergies and trade-offs in simultaneously dealing with these different objectives. Currently, industrialised energy systems are dominated by supply chains based on fossil fuels and these, for the most part, have been effective in enabling energy security and affordability. However, they are increasingly struggling to do this, particularly in respect to efforts to tackle climate change, given that the energy sector is responsible for around two-thirds of the global greenhouse gas emissions [1]. A key challenge is therefore how to decarbonise energy systems, whilst also ensuring energy security and affordability. This special issue, through a focus on supply chains, particularly considers the interactions and relationships between energy security and decarbonisation.

Energy security is a property of energy systems and their ability to withstand short-term shocks and longer-term stresses depends on other important system properties including resilience, robustness, flexibility and stability [2]. Energy systems are essentially a supply chain comprising of multiple and interrelated sub-chains based around different fuels, technologies, infrastructures, and actors, operating at different scales and locations – from extraction/imports and conversion through to end use [3]. These supply chains have become increasingly globalised and are influenced by the on-going shifts in global supply and demand. Thus the aim of this special issue is to explore and discuss how to enable the development of a secure and sustainable energy system through a better understanding of both existing and emerging low carbon energy supply chains as well as of new approaches to the design and management of energy systems. In part, because moving from a system dominated by fossil fuels to one based on low carbon creates a new set of risks and uncertainties for energy security as well as new opportunities.

A large number of submissions from over 18 countries were received for this special edition and 16 papers were accepted after peer review. These address a variety of issues and we have chosen to discuss the findings under two key themes, although many of the papers cut across these: (1) Insights from, and for, supply chain analysis. (2) Insights for energy security and its management. We then provide in (3) a summary of insights and research gaps. Table 1 provides a snapshot of the areas covered by the papers showing: theme (s); empirical domains; and geographical coverage.

1. Insights from, and for, supply chain analysis

Eleven papers provide insights into energy supply chains. A comprehensive overview of how to conceptualise supply chains as part of energy systems, as well as a detailed analysis of the supply chains for PV and nuclear power is provided by Hoggett [4]. This highlights the links between technologies and the wider co-evolving socio-technical systems in which they are embedded, as well as the risks that exist within the innovation system. A focus on the role of technology scale within a changing system is provided and it is shown that risks increase if a supply chain is reliant on a limited number of companies, technologies or markets and therefore that smaller scale technologies provide more resilience. The discussion from Genus and Mafakheri [5] uses a Neo-institutional framework to consider the development of bioenergy within the UK, providing insights on how supply chains evolve and the importance of non-technical issues. It describes how institutional processes and carriers enable and diffuse new rules that can impact on a supply chain. By looking at oil supply chains in China, the importance of the interactions between technical, socio-technical and institutions for policy processes are discussed by Guy et al. [6]. This uses a framework based on vital energy systems and securitization theory, which in part shows how powerful actors within the energy system can interpret problems and influence policy to suit their preferred outcome, specifically showing how the securitization of oil has dominated concerns at the expense of improving other supply chains.

Understanding risk is central to supply chains analysis and several papers provide important insights in this regard. Mulhall and Bryson [7] highlighted how energy is an essential input for firms operating within supply chains, particularly in respect to the impact that rising energy costs and price volatility can have on the stability of individual production companies and the wider supply chain in which they operate. Many supply chains have developed and operate on the basis of affordable energy, but global market dynamics are beginning to challenge this assumption. To reduce risks, firms and the wider supply chain they operate within increasingly need to develop strategies to manage price volatility across the whole supply chain. The need to consider supply chain risks dynamically to identify feedbacks and interdependencies from extraction to end-use are discussed by Gracceva and Zeniewski [8], through a focus on the interactions between energy and climate policy within the EU. Using a low-carbon scenario

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Table 1
Overview of paper themes, domains and geographic coverage.

Paper	Supply chains	Energy security	Domain	Area
Technology scale and supply chains in a secure, affordable and low carbon transition	✓	✓	Electricity	UK
A neo-institutional perspective of supply chains and energy security: bioenergy in the UK	✓	✓	Electricity heat	UK
Securitization of energy supply chains in China	✓	✓	Electricity	China
Sustainability of demand side supply chains	✓	✓	Demand	UK
A systemic approach to assessing energy security in a low-carbon EU energy system	✓	✓	All	EU
Biofuels for road transport: analysing evolving supply chains in Sweden from an energy security perspective	✓	✓	Transport	Sweden
Dynamic analysis of feasibility in ethanol supply chain for biofuel production in Mexico	✓		Transport	Mexico
Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply	✓		Electricity	US
Assessing the dynamic material criticality of infrastructure transitions: a case of low carbon electricity	✓	✓	Electricity	UK
Identifying critical materials for photovoltaics in the U.S.: a multi-metric approach	✓		Electricity	US
Challenges in assessment of clean energy supply-chains based on byproduct minerals: a case study of tellurium use in thin film photovoltaics	✓		Electricity	US
A multilayered analysis of energy security research and the energy supply process		✓	Electricity	Japan
Implications of paradigm shift in Japan's electricity security of supply: a multi-dimensional indicator assessment		✓	Electricity	Japan
Achieving sustainable supply chains through energy justice	✓	✓	Electricity	UK/ Denmark
Effects of renewables penetration on the security of portuguese electricity supply		✓	Electricity	Portugal
Towards smart grids: identifying the risks that arise from the integration of energy and transport supply chains		✓	Transport	Netherlands

alongside five key properties of energy security, it is shown that a low carbon transition will generate significant changes in virtually every major link and interdependency of the energy supply chain. The need to focus on the entire supply chain is also a feature of Månsson et al. [9] which examines the use of biofuels within Sweden. A methodology for supply chain analysis is set out covering technologies, resources, markets and investment to show how synergies can be gained by focussing on both the supply and demand side of a supply chain. Biofuels is also considered by Rendón et al. [10] who use a Systems Dynamic model to examine ethanol in Mexico and highlight the complexity, uncertainty and risks of disruptions for an emerging supply chain.

An integrated systems approach is used by Arent et al. [11] to examine the implications within the U.S. of moving to a system based on high levels of renewable electricity penetration, including its wider impacts for emission reductions, water and land use, and materials. Whilst it is found that there is considerable potential for ramping up renewable generation, with few negative impacts, the need for more research on short-term alternatives to rare earth elements for some critical technologies is highlighted, along with the need to carry out full life-cycle sustainability assessments for supply chain constraints. The need to understand the risks associated with critical materials is also explored in three other papers. Roelich et al. [12] discuss this in respect to infrastructure transitions for low carbon electricity using wind as a case study. Using a quantitative approach, it is argued that criticality can be defined in respect to the potential for, and exposure to, supply disruptions. Given the long time scale for infrastructure changes, risks should be assessed dynamically in terms of the materials needed for a technology, along with its rate of deployment, as there can be risks of potentially locking-in technologies that may face future energy security risks, if the materials needed for it become increasingly critical. Whilst Goe and Gaustad [13] use a multi-metric analysis for materials needed for PV within the US, suggesting that there are benefits associated with moving beyond assessments based on scarcity to include wider economic, environmental and supply risks as this will provide a greater range of strategies for dealing with short and long term supply risks. A further insight on criticality is provided by Bustamante and Gaustad [14] which, through a dynamic material flow analysis, examines the use of Tellurium in thin-film PV. This highlights that because this material is a by-product of copper production it creates additional complexities and risks for supply chains, as changes within the copper market or refining processes can create risks within the PV supply chain.

Collectively the above papers provide important insights for conceptualising supply chains, understanding the risks and bottlenecks they face, as well as ways to overcome them. They show how risks can impact individual firms, different technologies and fuels, as well as the supply chain as a whole; and the need to consider these issues in relation to the wider socio-technical systems in which they are embedded. For both low carbon transitions and energy security, analysis has to be dynamic and forward looking and there is a greater need to take a whole systems approach to such analysis.

2. Insights for energy security and its management

Energy security was also a central focus across the submissions and twelve papers provide a range of insights. Understanding threats and risks, and the ability of a system to deal with these, is central to energy security debates. Some of these risks result from short-term shocks to the energy system and a notable example within Japan was the Fukushima incident which two papers discuss. Firstly, Kiriyama and Kajikawa [15] discuss the need for a reassessment of the energy system and this is explored through a multi-layered analysis of energy security using a bibliometrics approach. This suggests that there has been a shift away from concerns over self-sufficiency in primary energy resources, towards diversification in the secondary supply chain including a growing role for energy networks and international cooperation. Also, that there is a need to bring in human security and resilience, in part because consumer lifestyle innovation will play an increasing role in security. Whilst Portugal-Pereira and Esteban [16] evaluate the security of Japan's electricity supply through a range of possible generation mixes that could support the country's energy security. Using a series of indicators and scenarios and a quantitative model this shows that significant change will be needed to provide reliability and that whilst a system based on renewables offers the best solutions there are infrastructure and technical constraints that will need to be overcome. It also shows the value of decentralisation in providing security and resilience. Both of these papers point to the need to engage end users with energy security and this issue is specifically explored by Heffron and McCauley