Supply chains and energy security in a low carbon transition

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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 important system properties to enable this 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 right 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.

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	✓		Electricity	US

U.S.: a multi-metric approach				
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 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	Nether-lands

Table 1: Overview of Paper Themes, Domains and Geographic Coverage

1. Insights from, and for, supply chain analysis

Eleven papers provide insights on 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 it operates. Many supply chains have developed and operate on the assumption that they can easily access affordable energy, but global market dynamics are beginning to change this. 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 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 U.S., 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 for other supply chains like PV.

Collectively the above papers provide important insights for conceptualising supply chains, understanding the risks and bottlenecks they face, as well as ways to overcome these. 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 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 [17]. This introduces the idea of energy justice, encompassing tenants of distributional, procedural and recognition justice. It is argued that through a focus on energy justice, improvements in collective decision making and responsibility between governments, society and the private sector can be achieved; and that this will ultimately lead to better policy decisions and outcomes for energy security, climate change, and supply chain development.

Risks to energy security also arise from long term stresses and several papers discuss this in respect to moving to a low carbon energy system. Within [18] Gouveia et al. consider the impact of growing amounts of variable renewables for balancing an energy system, through a focus on wind power within Portugal. Whilst on the one hand this has been seen as way to improve security, by reducing imports, it is also recognised that it has created new risks for the electricity system. However, these risks can be overcome through steps to increase system flexibility, including the use of interconnections to other countries as well as more effective grid management. The risks arising from measures to decarbonise energy systems are also highlighted by Eising et al. [19] who examine the issues for grid security from the uptake of electric/hybrid vehicles within the Netherlands using a GIS-based model. This analysis shows that efforts to decarbonise transport can create new risks for grid capacity and management, which need to be understood and mitigated. There can therefore be unintended consequences resulting from conflicts between different policy objectives as well as synergies, such as between decarbonisation and security". In looking at the EU Gracceva and Zeniewski [8] show how this can be understood by moving away from indicator based assessments of energy security, towards an approach based on the whole energy supply chain. As Roelich et al. [12] highlight, there can also be a risk of replacing one energy security concern with another. For the case of material criticality, which this paper discusses, this issue arises if the materials needed for a low carbon technology become increasingly more critical as a result of its large scale deployment. Conflicting policies are also highlighted by Månsson et al. [9] who show that whilst Sweden has been effective in decarbonising transport through a range of specific policies to encourage biofuels, energy security has not improved because imports have increased, this is because Sweden has not aligned its policies for decarbonisation and energy security.

Many of these issues relate to the uncertainties involved in enabling a secure low carbon transition and seeking synergies between policies to address decarbonisation and energy security will become increasingly important for policy makers. It is suggested by Hoggett [4] that a strategy for dealing with uncertainty is to focus on the ability of potential solutions to show characteristics of flexibility, adaptability and resilience, as this will reduce risks. Wider insights into the challenges of understanding, measuring and assessing energy security are provided in [4, 5, 8]; whilst the importance of understanding the historical context, system properties and institutional agents is discussed by Guy et al. [6].

Collectively, these papers provide important insights for understanding energy security, the factors that can impact it, as well as possible solutions for improving it. They reinforce the complex and multi-dimensional character of the problem and point to the need for on-going multi-disciplinary research to address it. As with supply chains, risk and the ability to deal with it are key areas, particularly in respect to dealing with shocks and stresses on a system, including those that arise from efforts to decarbonise energy systems.

3. New insights and research gaps

This special edition advances thinking about the links between energy systems and supply chains and their importance for energy security in a low carbon transition. There is a need for policy makers and wider actors within energy systems to take a whole systems approach that collectively consider supply chains, energy security and decarbonisation and options for aligning policy across these areas. This will better enable risks to be recognised, minimised and managed. Flexibility is a key way to reduce risks, including future price risk, and is therefore central to increasing system resilience. There is also a need to create the right conditions to both accommodate new technologies and fuels and to provide the space to deal with the uncertainties that system change creates. This could include steps to develop more integrated markets and interconnections between energy systems, as well as strategies to diversify supply and demand and re-engage end users with system change, energy security issues and the solutions to them.

In most industrialised countries energy systems are based on centralised energy models designed for the one way flow of energy, and there is a tendency for policy makers to focus attention on ensuring sufficient supply, almost regardless of the level of demand. Technologies, institutions and regulations have co-evolved and are now locked-in around fossil fuel supply chains creating path dependency and considerable inertia which is increasingly problematic for dealing with the energy trilemma. In addition, the governance frameworks that are currently in place are not attuned to the innovation and system change that is now needed to tackle climate change and ensure energy security. These issues collectively impact existing fossil fuel supply chains and the development of emerging low carbon technologies as well as the wider options for changing the design and operation of an energy system.

Based on the papers submitted to this special issue, electricity was the most common area of analysis, reflecting the importance of this carrier within low carbon transitions; whilst four papers discuss transport. Underrepresented areas include the heat sector, as well as analysis of the demand side, which could play an increasingly important role in providing system flexibility. In addition, although several papers noted the importance of enabling technologies like smart grids and energy storage, as well as options for reducing the impact of fossil fuels like CCS, these issues were not explored in detail, even though they could have significant implications for supply chains and energy security. There was also a limited focus on what we consider to be some key potential supply chain bottlenecks, including skills and training, finance and investment, and the rules and regulations that govern and shape the design of markets and energy systems. Further analysis from emerging economies would also help to broaden the breath of the analysis.

Much more work is needed to further explore these issues, included developing stronger links and joint analysis with the wider body of experts working within the supply chain world. The analysis put forward within this special edition, including through the various models, conceptual frameworks and scenarios, provide insights to better understand and reduce risks for supply chains, energy security and low carbon transitions. They also show the complexities and interactions between these areas. There is considerable scope for further research to better conceptualise and understand the issues and opportunities for enabling the sustainable and secure development of energy systems, including the role of governance in terms of the extent to which desired systemic proprieties like flexibility, robustness and resilience can be delivered through the market or forms of strategic intervention. There is also a need for more interdisciplinary approaches that consider quantitative analysis of supply chain challenges and more qualitative analysis of risks, trade-offs, and non-technical barriers/issues. This could include a more systematic mapping of all energy supply chains, possibly through a common socio-technical risk assessment framework.

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