The causes of risk in fuel supply chains and their role in energy security

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Highlights

- We propose a transparent risk assessment method for energy security analyses.
- Our method identifies drivers of systemic risk in fuel supply chains.
- We conceptualise risks as having micro-, meso-, or macro-scale effects.
- Main risks: access to capital, changing policy/regulation, and public concern.
- Our method is robust to uncertainty in individual risk scores.

Abstract
Managing risk is of central importance in achieving energy security, yet a methodology for identifying and assessing all relevant risks has previously been lacking. From an extensive review of risk and the operation of fuel supply chains, 34 distinct generic causes of risk have been recognised. These risks were analysed for the UK's energy system, considered as 19 fuel supply chains (each with six stages), and scored by likelihood and impact on the supply chain (accounting for resilience). A risk matrix was constructed recording the risks encountered at each stage for each fuel. For the UK, the three causes with the greatest total score were 'lack of access to capital', 'changing policy or regulatory framework' and 'significant public concern', all of which were amongst the eight causes of risk noted as most significant at an expert verification workshop. This methodology yields a credible and direct quantification of risk for a national energy system – an indicator of energy security. It does not require the assignment of weighting factors to various contributory characteristics, often arbitrarily chosen in other approaches. It is suggested that the seven most prevalent causes of risk, that occur for nearly all fuels and all stages, may be systemic in nature. The method offers sufficient flexibility to make it readily applicable to other nations, regions, or sites, and other types of supply chain.

1 Introduction

Increasing awareness of the effect of rising atmospheric concentrations of carbon dioxide on the global climate led to international agreement that the use of fossil fuels should be reduced (IPCC, 2015). Such a radical alteration to the systems providing energy to the world's population is a huge undertaking, involving the rapid introduction of renewable energy sources. Understandably, this raises questions about how and when changes could and should be made, and their scale of impact. This in turn leads to the key question of their effect on energy security (García-Gusano et al., 2017; Olz et al., 2007).

Measuring and tracking energy security has been of interest to nations and national blocs as the global economy has grown with increasing reliance on internationally traded fuels. Indeed, many methods of assessing energy security focus solely on security of supply, and particularly on the risks of interruption to the supply chains of fossil fuels. However, this limited view of energy security is insufficient given the ambition to switch away from reliance on coal, oil and natural gas. Some attention to a wider perspective of energy security was recognised by Gasser (2020) in his review. As Gasser noted, the definitions of energy security proposed by international organisations (APERC, 2007; EC, 2014; IEA, 2014) included as common elements the physical availability and accessibility of supply sources, their economic affordability but also their long-term environmental sustainability.

The concepts of sustainability and energy security share some common features (Axon and Darton, 2021a). They both aim at a desirable way of using resources, either meeting needs of the present without compromising the ability of future generations to meet their own needs, for sustainability (United Nations, 1987), or meeting energy needs in a low-risk (dependable) manner, for energy security.

The importance of managing risks which may interfere with our ability to meet our energy needs has been remarked by energy security researchers, since "*more secure systems are those with lower risks of system interruption*" (Lieb-Dóczy et al., 2003). But, perhaps surprisingly, even when risk is mentioned, it is often poorly treated in the energy security literature (Axon and Darton, 2021a). For example, it is frequently represented in assessments by some system characteristic that is only loosely associated with either risk or resilience (the ability to cope with risk events). Gasser reviewed 63 indices which aimed to measure national energy security, commenting on the arbitrariness of the selection of characteristics included, and also on the lack of transparency in the methods of normalisation, weighting and aggregation of the chosen indicators (Gasser, 2020). The lack of a coherent framework for identifying and quantifying risks inevitably leads to omissions and inconsistencies, which may explain why indicators of energy security have had little effect on policy development (Chester, 2010; Kruyt et al., 2009). We aim to address this issue using an approach which identifies and uses causes of risk to inform energy security assessments.

The broad literature on risk in supply chains has been reviewed by Gurtu and Johny (2021) who noted that whilst some risks are common, not all supply chains are subject to the same risks. They emphasise the role of published literature in helping to identify risk factors needing management attention. We have made thorough use of literature to identify sources of risk, but as our objective is to assess energy security, not to manage risk, our approach is tailored to this end. Tang and Nurmaya Musa (2011) noted that most of the literature on supply chain risk management lacks a quantitative approach, dealing only with some part(s) of the supply chain and limited causes of risk. Our methodology seeks to identify *all* significant risks in the operation of *each* complete fuel supply chain, and quantifies their impact in that context. In this way it is possible to locate and rank the various risks, which enables us to evaluate the total risk in each chain. Arbitrary weighting of different risks is avoided by assessing their impacts on a common scale.

In this paper we first discuss the background to the causes of risk commonly appearing in the energy security literature. We then present our methodology to place the causes of risk in an analytical framework (section 3). Section 4 deals with a case study of the UK, and section 5 presents details of an expert workshop on causes of risk. Finally, we draw conclusions, outline topics for future research, and suggest some others areas to which our method can be applied.

2 Background

The sources of risk most often mentioned in connection with energy security are those which can readily and abruptly disrupt energy supply, namely conflict / war, engineering failures, accidents, sabotage, natural disasters, or market volatility (Chester, 2010), but frequently these are debated quite separately from each other (Winzer, 2012). For example, there is a considerable body of literature dealing with the risks arising from high import dependency and the perceived remedy of reducing imports, or diversifying sources of supply (Cherp et al., 2016; Jansen et al., 2004). However, the benefits of diversification of supply are not clear-cut, and a focus on global political issues may be distracting attention from other energy security issues that are micro in nature (Metcalf, 2014). Specific risks in fuel supply chains have been noted, including delay/loss of shipment due to piracy, infrastructure operational failure (port, ship, pipeline), price volatility, extreme weather event, accident (explosion, fire, leak), and problems with political/economic relationships with trading parties (Sun et al., 2017; Zhang and Bai, 2020). Hammond and Waldron (2008) recognised the importance of understanding risk for energy systems and made a thorough assessment of the UK's electricity supply network, grading fifteen specific risks according to their impact and likelihood. Concerns about the security of Europe's electricity systems are seen as economic risks due to under-investment and rising demand, together with risks of natural calamities and severe weather (Nepal and Jamasb, 2013). The growth of digitalisation and the transition towards a smart grid (Balta-Ozkan et al., 2014, 2020) are increasing the risk of cyber-attacks (Kisel et al., 2016) amongst the external threats to which the electricity sector should be resilient (Connor et al., 2018), together with acts of terrorism, natural disasters and the effects of climate change (Kisel et al., 2016).

By focussing on security of supply, Winzer (2012) distinguished three broad categories of sources of risk: *technical* (failure of components or systems due to malfunction or human error), *human* (behavioural or political actions like demand fluctuations, supply embargoes, under-investment, terrorism and war), and *natural* (resource intermittency and depletion, floods and earthquakes and other natural disasters). The World Economic Forum suggests five general categories of sources of risk in its annual surveys: economic, environmental, geopolitical, societal and technological (WEF, 2021). These were used to drive an analysis of some 30 global risks affecting food, water and energy security (de Amorim et al., 2018).

Metcalf (2014) suggested that from an economic point of view, the United States would be better protected from energy price shocks by reducing demand than by reducing imports. Accordingly, relevant risks to energy security would include those undermining investment in energy efficiency, such as falling energy prices. Winzer also identified the critical importance of adequate infrastructure and the necessary investment for it, an issue underlined by others (Winzer, 2012). Risks in the innovation of new and renewable technologies have been analysed (Foxon et al., 2005), and for carbon capture and storage (Markusson et al., 2012); the importance of appropriate government policy to help manage innovation risk seems clear (Samant et al., 2020).

Governments have to devise strategies for managing risk in many sectors, including the provision of energy and energy services. Amongst eight principles for guiding government policy on risk Aven and Renn (2018) advise:

- that the proper risk level, which is context-dependent, needs to be arrived at by balancing different concerns using a value and evidence/knowledge-informed process;
- supplementing formal analyses with broader judgments of risk, as well as stakeholder involvement;
- managing risk using risk-informed, cautionary/precautionary and discursive strategies to develop more risk- and dialogue-oriented policy styles;
- openness and transparency with the public about risks and the processes in use to handle them.

These principles offer useful pointers to improving the treatment of risk in energy security. In particular we conclude that it is essential to identify clearly the risks across the whole national energy system and assess their severity directly using a defined and transparent process. This is necessary to facilitate informed dialogue between stakeholders, policymakers and public. Meaningful dialogue and appropriate policy formulation will be difficult if all the significant risks and their causes are not properly recognised and assessed.

Good institutional governance requires organisations to keep an inventory of risks – a risk register – with a view both to mitigation, and emergency planning. The UK's national risk register for example gives an illustrative list of high-consequence risks, including attacks of various descriptions, pandemics of infectious disease, coastal and inland flooding and major industrial accidents (Cabinet Office, 2017); this list is accompanied by narrative explaining the risks and potential responses. When drawing up a risk register, the essential criterion is one of completeness – to ensure that ALL activities and risks are screened so that all important risks have been identified.

The requirement for completeness, and the need to screen a diverse range of activities to identify their impacts is also a common feature of methods for appraising sustainability. We have therefore adopted and adapted a methodology developed for sustainability assessment – the Process Analysis Method (Darton, 2017). In this method the impacts of system processes on the three stores of value (environmental, human/social and economic) are identified and quantified, to give an overall measure of sustainability through a set of indicators. In the Risk Assessment Method (Axon and Darton, 2021b), the triple-bottom-line assessment of impacts is retained, but the key difference is that the impacts considered are those of risk events perturbing system processes. The indicators (plus metrics) measure overall risk, rather than overall sustainability.

When applying the Risk Assessment Method to measure energy security, the national energy system is decomposed into staged supply chains for different fuels. In a case study of the UK, each fuel supply chain was screened to identify risks, and the severity of the risk impacts was judged, using a consistent scale. This produced a ranking of the overall risk level of the 19 fuels (Fig. 1) relevant to the UK energy economy. It also mapped risk severity in the fuel supply chains identifying the activities incurring the greatest risk (Axon, 2019).

At the heart of the Risk Assessment Method is the systematic and comprehensive identification of risks in the fuel supply chains that comprise the energy system. In the present publication we examine how these risks can be identified and assessed to build up a detailed picture of risk as it affects energy security.

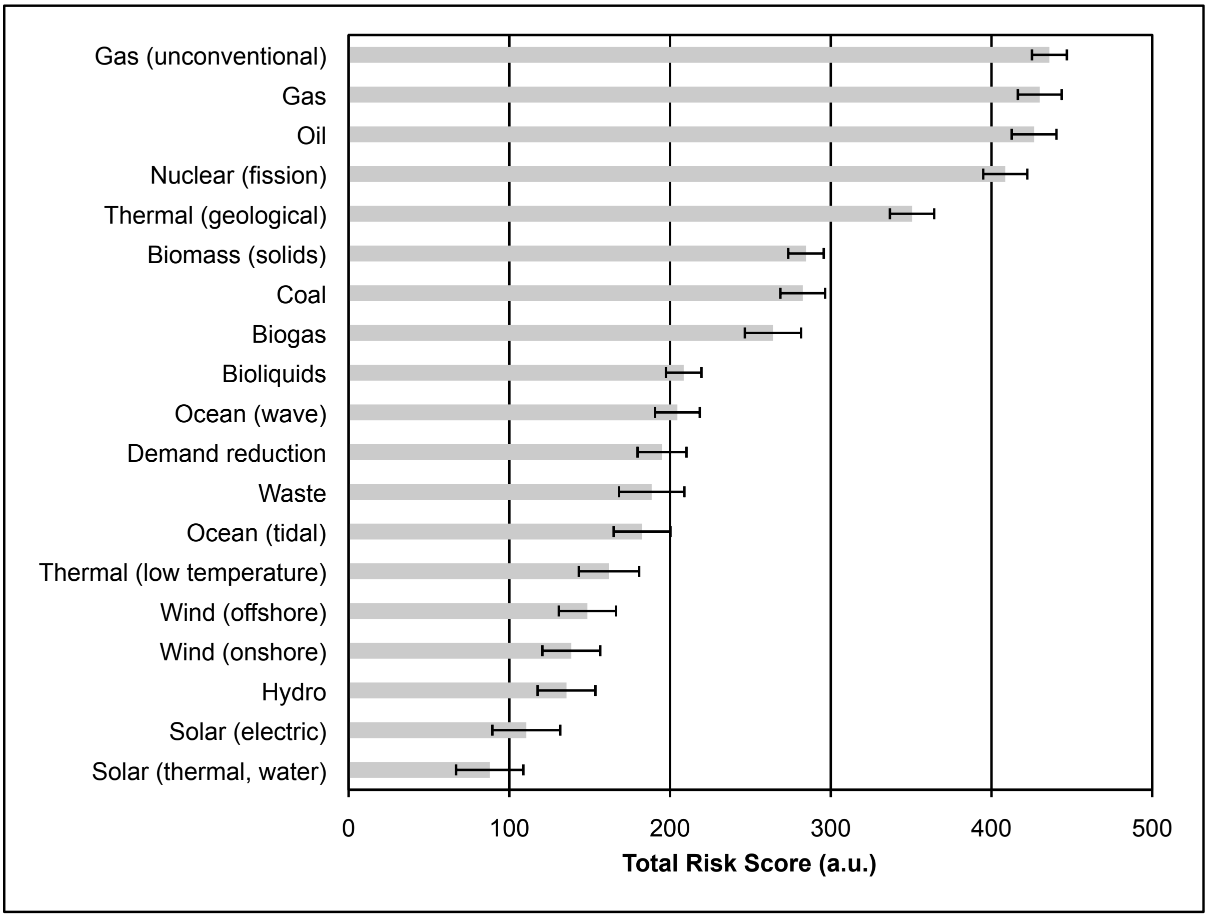

Fig. 1. UK case study. The total risk score (absolute units) for all fuels with a worst-case error of ΔR=2 for each individual cause of risk for each fuel at every stage. The derivation of the uncertainty score is given in Appendix A. Source: (Axon, 2019).

3 Methods

The Risk Assessment Method uses an assessment framework which is first developed and checked, and then applied to a case study (Fig. 2) (Axon, 2019). The framework is designed to be independent of the characteristics of the nation or fuels to which it will be applied, though these affect the specific risks that need to be considered in the case study. The risks are viewed as those acting as a threat to the ability to meet national energy needs (maintaining the supply/demand balance). The threat is to the energy system under consideration, this is the nature of a comprehensive approach to risk assessment.

The energy system was decomposed into 27 subsystems each for the supply and use of a distinct fuel. Each fuel supply chain was considered as a sequence of six stages, exploration-exploitation-conditioning-conversion-distribution-use, though some stages were not relevant for some fuels. One of the fuels, Demand Reduction, was conceived as 'negative fuel' acting to satisfy the supply/demand balance through improved energy efficiency and change in behaviour.

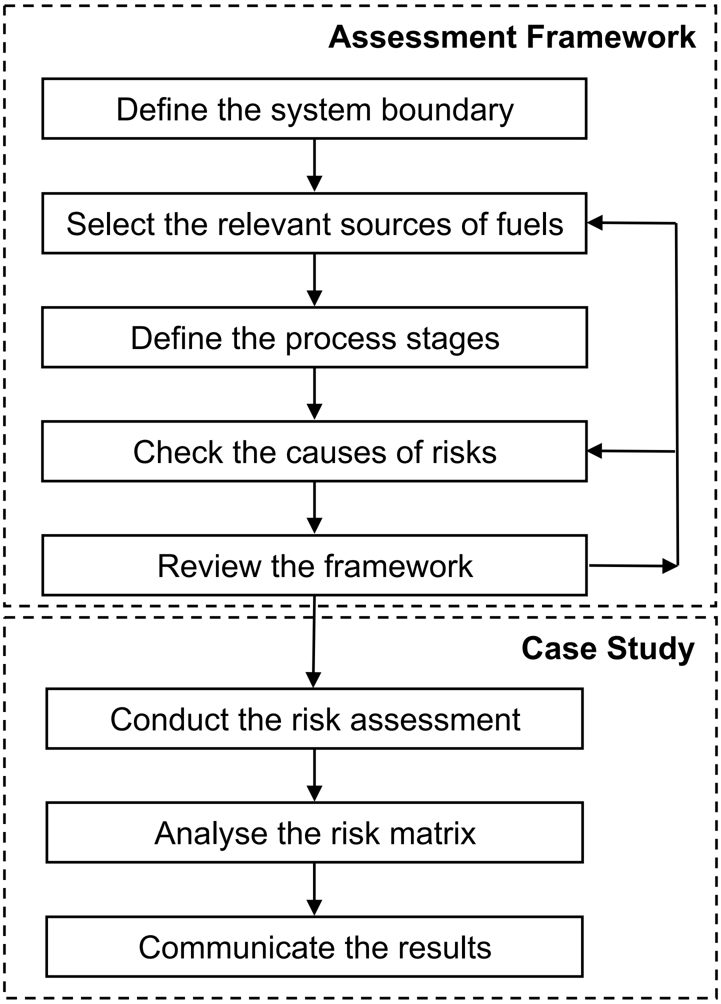

Fig. 2**.** The steps taken to conduct the assessment and case study.

3.1 Identifying Causes of Risk

The term 'risk' is frequently encountered in literature relating to the management of safety and security, where it can have a variety of meanings. In general, we follow the Oxford Dictionaries in understanding risk as *"(Exposure to) the possibility of loss, injury, or other adverse or unwelcome circumstance".* Additionally, we note the proposal of Vlek (2013), writing of the construction of national risk registers, that risk may be conceived as *"…an insufficient potential to meet external harmful demands"*. Vlek explains that the impact of a risk event will commonly be experienced according to the sufferer's ability to cope and recover. We use this idea of resilience and recoverability in gauging the level (magnitude) of impacts (Table 8).

A fuel supply chain which takes energy from locating and exploiting its source (such as oil well or wind turbine) to end-use (in a farm, factory, motor car or home, say) involves a very wide range of risks. Amongst these, the risks of disturbance due to political instability and price volatility are often cited in the literature, as are the threats of interruption due to technical failure or natural disaster. However, there are many other risks which attract fewer headlines, but which can be significant, nevertheless. The risks that are relevant are those which pose a threat to the ability of a nation to meet its energy needs in a dependable manner, that is, its energy security. Risks which may cause harm that would have little or no effect on energy security are excluded.

To identify all relevant risks in the energy system we started with the structure of the energy system as staged fuel supply chains (Axon and Darton, in review). Considering each chain in turn, we used a broad range of literature to identify risks and risk events, at each process stage, which could interfere with its ability to function either in the short, medium or long term. The literature that contributed to this analysis can be broadly described as follows:

- general methods for risk (risk theory, risk metrics, risk management, risk codes and standards, risk in non-energy industries, risk registers, systemic risk, risk in supply chains) 147 items,
- energy security (general approaches, security of supply, national assessments, indicator sets, energy system resilience) 161 items,
- specific causes of risk in fuel supply chains 179 items.

Reviewing risk metrics suitable for decision support in the field of health and safety, Johansen and Rausand) (2014) proposed that they should satisfy (most of) 11 criteria, namely with respect to validity, reliability, transparency, unambiguity, contextuality, communicability, consistency, comparability, specificity, rationality, and acceptability. These criteria guide our selection of an appropriate set of 'causes of risk' from those identified in the literature (more than 80). Our experience with constructing sets of metrics to characterise complex systems using the Process Analysis Method suggested that the number of generic 'causes of risk' might total perhaps forty or less. After analysing several chains and refining the method (Fig. 2) we recognised 34 distinct causes of risk. Relevant risks in all the supply chains could be attributed to one of these 34 causes. Candidate causes of risk were discarded for reasons including relevance to only one fuel or geographical location, or applicability only to particular projects.

Some of these risks are known from the energy security literature, where they are described and discussed, but many more have received little formal attention, not having formed part of any common view of what constitutes energy security. We note that not all causes of risk will lead to a specific risk for all fuels and all stages. The 34 causes of risk can be conveniently grouped in seven categories, having characteristics that are related, broadly, either to Economic, Environmental, Innovation, Manufacturing, Political, Skills, or Technical issues. These seven categories of risk are likely to be similar when examining the functioning of a supply chain for any engineered product. We emphasise that the categories are assigned for convenience of presentation only, it is the individual causes of risk which are important and distinct (avoiding duplication or overlap of concepts). The complete list is given in section 2.2 where its role in generating the risk matrix is explained.

3.2 The Causes of Risk and their interpretation

For each of the seven categories of risk the desirable features for the energy system are briefly described below, together with typical causes of risk and questions to help in interpretation (Tables 1-7). Since we need to judge the level of each risk, it is important to take account of its context (stage) and the supply chain resilience with respect to a risk event.

Economics (Table 1)
Desirable features: The levels of macroeconomic activity and stability are important. The provision of capital is required for all scales of energy systems. The return on investment (ROI) should be stable and predictable for a time well beyond the payback period. Competition in any relevant markets needs to be fair – the market needs to be well-functioning.

Nature of the risk: Lack of predictability leads to uncertainty (Jones, 2015; Mazzucato and Semieniuk, 2018). In turn this affects access to capital since the projects are large (relative to the size of the borrower) and instability during the payback period is unacceptable (Oxera, 2011). For commercial schemes, without a reasonable ROI, access to capital is likely to be restricted (Egli, 2020; Gross et al., 2010).

Table 1.
Economic risk: typical causes, independent of fuel and stage.

Cause of Risk	**Interpretation**
Lack of a well-functioning market	Are there plenty of suppliers for equipment, components, systems, or services for the required activities? Or is there evidence of monopolistic market actors?
Lack of access to capital	Are the required components, systems, or services considered as mature or immature, or how significant is the investment compared with normal business operations?
Unable to agree a price for licence or permits	Is the price of permits for access, extraction, siting, or disposal of waste a significant proportion of operating costs?
Uncertain decommissioning costs	If the decommissioning costs are unknown, what is the impact on the viability of the activities?
Price volatility	How significant is volatility in the price of equipment, components, systems, or services for the required activities?

Environment (Table 2)
Desirable features: The stability and predictability of the environs of a scheme and the long-term stability of the climate are highly desirable (minimal likelihood of catastrophic natural hazards). The environment is the provider of the natural resources – fuels, water and minerals – required for the energy supply chains under examination. (These can be termed 'ecosystem services' but for many fuels the only ecosystem service to be supplied is water. Therefore, we refer to water-use explicitly, and account, where required, for biotic ecosystem services as a variability in the quality of the fuel source - e.g. for exploitation of biofuels - with the consequences cascading through the subsequent process stages.

Nature of the risk: The continued use of fossil fuels is likely to lead to changes in the climate with impacts on the near- and long-term. The depletion of resources is a risk to all fuel supply chains (Stamford and Azapagic, 2012), but more acute for some (Murrant et al., 2015; Speirs et al., 2015). Over-extraction of a resource may lead to the loss of ecosystem services (Dockerty et al., 2014). The environment will present unpredictable natural hazards.

Table 2
Environmental risk: typical causes, independent of fuel and stage.

Cause of Risk	**Interpretation**
Difficult physical access	Is the site physically remote or with difficult terrain?
Natural hazards	Is the site subject to significant natural hazards?
Quality of fuel source	How significant is resource composition variability, including ecosystem services, on the required activities?
Lack of water availability	How dependent are the activities on water availability?
Lack of critical materials availability	How important is the availability (current or projected) of critical materials for the activities?

Innovation (Table 3)
Desirable features: The extraction and processing of fuels currently used (either bulk or niche) require on-going incremental technical development. For unconventional fuels or new sources, innovation is essential if new devices to extract and exploit are to be developed successfully. Innovation of business models and structures are also important.

Nature of the risk: The inability to solve problems. A new device or process may not be scaled to a size that makes any significant difference, or be economically viable, or it may not be possible to engineer a practical, safe, and reliable commercial system (Anadón et al., 2017; Foxon et al., 2005). Market structures and regulation may prevent new opportunities developing (Connor et al., 2018). For mature technology, systems, processes, or business models the risk lies in competition from innovation (Hanna et al., 2015).

Table 3
Innovation risk: typical causes, independent of fuel and stage.

Cause of Risk	Interpretation
Weak technology transfer environment	Are there many opportunities for a new technology or practice to be deployed? Hard for niche or small-scale activities.
Lack of public subsidy	Would the R&D cease if no subsidies were available?
Only marginal improvements likely	Is the technology required mature with a history of only incremental improvement i.e. near the top of the S-curve?
Lack of material substitutability	Are the technologies dependent on the properties of particular materials?
R&D capacity or capability does not match the challenge	Are the barriers to start R&D so high that only large organisations can afford to participate? Is there a vibrant R&D landscape for the technology in question?
Optimism bias	To what extent does optimism bias of future improvements in technologies and efficiency gains over-inflate the value placed on the likelihood of an activity remaining competitive or becoming mainstream?

Manufacturing (Table 4)
Desirable features: The manufacturing sector must have capacity to construct facilities and processes, with global resilience i.e. multiple specialist manufacturers. This point of resilience is different from there being competition amongst manufacturers – it is necessary to avoid a single point of failure geographically. Manufacturers should use resources efficiently and operate safely with respect to the workforce and the environment.

Nature of the risk: Lack of resilience (Zografopoulos et al., 2021) caused by too few centres of manufacturing expertise (capacity) (Sandor et al., 2018).

Table 4
Manufacturing risk: typical causes, independent of fuel and stage.

Cause of Risk	Interpretation
Insufficient capacity to manufacture system components or conversion devices	Is there sufficient manufacturing capacity to meet demand? (Not a question of competition.) How significant to global capacity would be the loss of some manufacturing facilities?
Insufficient capacity to construct sites	How significant are demands (scale, complexity, number) for constructing the extraction, processing, or conversion sites?
Insufficient rate of infrastructure construction	What is the impact on the activities if new infrastructure (including ICT) is not put in place?

Political (Table 5)
Desirable features: These requirements are in line with standards suggested by the World Bank (2018). The political system should be incorruptible. Stability is a key factor, both in terms of public safety and

the socio-legal system. Specifically, in relation to investment in energy systems, stability of the policy environment and the regulatory framework are both needed. The legal system needs to be fair and robust, with an independent judiciary able to protect rights of property and provide prompt and fair dispute resolution. The system of taxation should be predictable and transparent. The legislature sets or adopts safety and employment laws, which should be enforced equally in all workplaces. Internationally acceptable ethical standards of behaviour (employment, legal, fiscal, etc) in public life are required. The nation being assessed should have normal international relations and not engage in violent internal suppression or external aggression i.e. the absence of violence. Public protest must be allowed, but the safety and security of both energy system sites and the public should be protected. NGOs should be allowed to campaign openly. Actions of the public should also be considered as they are part of the polity. The 'political risk' category includes both nations within the system boundary and those externally from which fuels and other relevant goods and services are sourced.

Nature of the risk: Political instability leading to unrest could prevent (parts of) a fuel supply chain operating in a specific country or region (Alorse et al., 2015; Lu and Thies, 2013). Instability also arises from a changing regulatory or policy framework (Campbell, 2015; Keay, 2016; Li and Pye, 2018). Both have an impact on operations and investment decisions. The presence of corruption or other unethical behaviours is a risk. Public protest poses a risk to the 'licence to operate' (Chilvers et al., 2017; Parkes and Spataru, 2017).

Table 5
Political risk: typical causes, independent of fuel and stage.

Cause of Risk	Interpretation
Denial of permission to access sites	What impact if an individual, company, or Government were to prevent access to a specific site or region?
Lack of social stability	Is there political unrest, threatening physical security of the workforce or assets?
Changing policy or regulatory framework	How significant would be (or has been) the impact on activities caused by changing relevant laws, regulation, or policy direction?
Poor institutional governance	How significant is the concentration of activities in regions with weak governance (corporate or legislative), elevated levels of corruption, or poor law enforcement? How much confidence in the legal system to uphold agreements?
Disputed land rights or resource ownership	How significant is the concentration of activities in regions with disputed land rights or ownership of resources?
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Are current regulations likely to be enforced and is there a record of improvement? This includes standards for vehicle emissions, quality and consistency of product, health and safety, and buildings codes.
Significant public concern	Protests (physical or online) against an activity representing each stage.

Skills (Table 6)
Desirable features: The operation of sites and processes requires human skills from basic manual tasks to specialised technical design and engineering expertise. The education sector should produce the variety of skills needed and sufficient numbers of people (capacity). The educated workforce should be flexible and the quality of basic and advanced qualifications be reliable.

The nature of the risk: Skills provided by workforce lacking in availability, flexibility, and quality (Engineering UK, 2018; Gooding and Gul, 2017; Jagger et al., 2013).

Table 6
Skills risks: typical causes, independent of fuel and stage.

Cause of Risk	Interpretation
Lack of basic education levels in the local workforce	At the location of the activities, is there a sufficient supply of working-age citizens with basic numeracy and literacy?
Lack of vocational training of the local workforce	At the location of the activities, is there a sufficient supply of citizens trained with appropriate practical skills?
Lack of specialists in the local workforce	At the location of the activities, is there a sufficient supply of citizens with specialist skills or is it easy to persuade such people to relocate?

Technical (Table 7)
Desirable features: The energy system should be reliable and with sufficient capacity to offer resilience when plant or infrastructure have planned or unplanned outages. The system should be safe with respect to the workforce and the environment.

Nature of the risk: Human error, sometimes due to inexperience, in design, operation, and management, is the cause of technical risk (Burgherr and Hirschberg, 2014; Sovacool et al., 2016, 2015). Consequences may be financial loss, wasted resource, injury and death, or a pollution event (Barker and Wood, 1999; Heede and Oreskes, 2016). Although a lack of resilience in technical systems is in part due to design errors, constraints may have been imposed from decisions in other categories.

Table 7
Technical risk: typical causes, independent of fuel and stage.

Cause of Risk	Interpretation
Pollution event	How much impact from operational pollution events on the environment (including ecosystem services)?
Unable to neutralise waste at decommissioning	If the waste cannot be made safe at the decommissioning stage, what is impact on the long-term viability of fuel source?
Specialist equipment unavailable	How much impact or delay would the lack of specialist equipment have on activities?
Operational failure	How much impact would an outage of a major facility have on the activities? The cessation of production may be due to equipment failure, human error, or management failure.
Infrastructure failure	How much impact would an outage of a major infrastructure link have on the activities? This could be failure of transport, transmission, distribution, ICT, or discovery of an equipment design flaw.

3.3 Scoring the Risks

The risk matrix records the risk assessments (Axon and Darton, 2018). Once the most relevant causes of risk are identified for each stage, the specific issues for the nation or bloc within the system boundary are incorporated using the levels of impact and the likelihood. The method of scoring a risk is to calculate the likelihood score multiplied by the impact score (Risk = L x I), following the rules for risk matrices (Baybutt, 2016; Cox, 2008; Levine, 2012; MacKenzie, 2014). This avoids the problems such as ranking reversal, which can be encountered with poorly designed risk matrices. The levels and descriptors are shown in Table 8. Our matrix (Axon, 2019) consists of the risk score, the location of the cause of risk (inside or outside of the system boundary), a note to remind the reader of the main technology or activity for which the risk assessment is being made, and the scale at which the risk manifests. An extract of the exploitation stage for five fuels in the UK case study is given in Table 9 as an illustration. Each likelihood-impact pair is assessed using data (where possible) and expert assessments from literature; full details of the literature used and the individual assessments is given in Axon (2019). Assessment was facilitated by the way in which the consequence table (Table 8) is constructed. The analysis of error propagation (Appendix A) shows that the overall score for a fuel is not sensitive to misattributed scores for likelihood and impact.

The assessment of the likelihood and impact score for each risk must be carried out in the context of the activity (at each stage for each fuel) for the case study. This makes sense since the raw fuel usually is processed to an intermediate product, then converted to a final energy vector. The same risk may occur at more than one stage, but this is not double-counting because the activities by which the risks manifest may be different. Not all risks are relevant at every stage for every fuel. There are two steps for identifying which causes of risk need to be considered for each stage:

1. Does the cause of risk have an impact on whether the activities in the stage can proceed or not? If there is little likelihood of the cause of risk stopping or hampering the activity, it is unlikely to be a relevant cause of risk for that stage.
2. If the level of the cause of risk were to fluctuate up and down without having an impact, then it is unlikely to be a relevant cause of risk for that stage.

Causes of risk which are not fully relevant to at least one fuel at a particular stage are eliminated from consideration at that stage. The scale of the risk is also important when considering which causes are most relevant. For example, a pollution event may occur at the exploration stage, but because any exploration scheme is small by definition any spillage or escape of resource into the environment will have a limited impact on whether a project proceeds or not.

Table 8

Risk scores assigned on the basis of Impact (scores 1-4) and Likelihood (scores 1-3). After (Axon and Darton, 2018).
Consequence level is assigned as High Medium Low

		Likelihood Level and Descriptor		
		Rare (1)	Possible (2)	Likely (3)
Impact Level and Descriptor		Only occur in exceptional circumstances << once per 10 y	May occur Once per 10 y	Expected to occur Once per 1 y
Insignificant (1)	Any impact is only at edge of normal or accepted operation.	1	2	3
Minor (2)	Recoverable short-term loss of activity, delay, or function.	2	4	6
Moderate (3)	Recoverable, but sustained delay, loss, or change in function.	3	6	9
Major (4)	Irrecoverable change or loss of function or enforced cessation of activity such as complete loss of fuel source, loss of life, closure of business / site / operation.	4	8	12

Table 9

UK Case study: a section of the risk matrix, for five fuels at Stage 2. A greyed-out entry indicates that the cause of risk is not relevant for that fuel at the exploitation stage. Risk scores colour-coded as in Table 8. The 'Principal Means or Technology' descriptors characterise the most important high-level element of that stage i.e. the technology used or the means by which activities occur. The 'Principal Risk Location' descriptor notes the location of the activity.

Stage 2: Exploit	**Fuel Category**	**Bioliquids**				**Demand reduction**				**Gas**				**Nuclear (fission)**				**Thermal (geological)**				**Thermal (low temperature)**				**Wind (offshore)**			
	Principal Means or Technology	**Gather energy & waste crops**				**Create dev, serv & comm camps**				**Drill**				**Mine**				**Drill**				**Operate HP**				**Operate turbine**			
	Principal Risk Location	**UK**				**UK**				**Global**				**Global**				**UK**				**UK**				**UK**			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Meso	2	1	2	Meso	2	3	6	Macro	1	2	2	Macro	2	1	2	Macro	1	2	2	Macro	3	2	6	Macro	2	1	2
Lack of access to capital	Economic	Meso	2	2	4	Meso	2	2	4	Macro	2	3	6	Macro	3	4	12	Macro	3	4	12	Meso	3	3	9	Macro	1	2	2
Unable to agree a price for licence or permits	Economic				0				0	Meso	2	2	4	Meso	1	2	2				0				0	Meso	1	4	4
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	1	1	1	Micro	2	3	6	Micro	3	2	6	Micro	2	2	4	Micro	2	1	2	Micro	3	1	3
Price volatility	Economic	Macro	1	1	1	Meso	1	1	1	Macro	2	1	2	Macro	2	2	4	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2
Difficult physical access	Environmental	Micro	1	1	1				0	Micro	3	3	9	Micro	2	2	4	Micro	1	2	2	Micro	2	1	2	Micro	3	2	6
Natural hazards	Environmental	Micro	1	2	2				0	Micro	3	4	12	Micro	1	2	2	Micro	2	1	2				0	Micro	2	2	4
Quality of fuel source	Environmental	Micro	1	1	1				0	Micro	2	1	2	Micro	2	2	4	Micro	2	4	8	Micro	1	1	1	Micro	2	2	4
Lack of water availability	Environmental	Micro	2	2	4				0	Micro	1	2	2	Micro	3	2	6	Micro	2	1	2				0				0
Lack of critical materials availability	Environmental				0	Macro	2	1	2	Macro	1	1	1				0	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4
Weak technology transfer environment	Innovation	Meso	1	1	1	Meso	2	2	4	Macro	1	2	2	Macro	1	1	1	Macro	1	2	2	Macro	2	2	4	Macro	1	1	1
Lack of public subsidy	Innovation	Meso	1	1	1	Meso	2	3	6	Meso	2	1	2	Meso	1	1	1	Meso	2	3	6	Meso	3	2	6	Meso	2	2	4
Only marginal improvements likely	Innovation	Macro	2	1	2	Meso	1	2	2	Macro	2	2	4	Macro	3	1	3	Macro	2	2	4	Macro	1	2	2	Macro	3	1	3
Lack of material substitutability	Innovation				0	Macro	2	1	2	Macro	1	1	1				0	Macro	2	1	2	Macro	1	1	1	Macro	2	3	6
R&D capacity or capability does not match the challenge	Innovation	Macro	1	1	1	Meso	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	3	1	3	Macro	2	2	4
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Macro	2	1	2	Macro	1	1	1	Macro	3	3	9	Macro	2	2	4	Meso	1	2	2
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1	Macro	1	1	1	Macro	2	1	2	Macro	1	1	1	Macro	2	1	2	Macro	1	2	2	Macro	2	2	4
Insufficient capacity to construct sites	Manufacturing				0	Micro	3	3	9	Macro	2	1	2	Micro	1	1	1	Meso	2	2	4	Micro	2	2	4	Meso	2	3	6
Insufficient rate of infrastructure construction	Manufacturing	Meso	1	1	1				0	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	4	8	Meso	3	4	12
Denial of permission to access sites	Political	Micro	1	2	2				0	Meso	2	1	2	Micro	2	2	4	Micro	1	1	1				0	Meso	2	3	6
Lack of social stability	Political				0				0	Meso	2	4	8	Meso	2	2	4				0				0				0
Changing policy or regulatory framework	Political	Meso	1	1	1	Meso	2	2	4	Meso	1	2	2	Meso	1	2	2	Meso	3	3	9	Meso	3	3	9	Meso	2	4	8
Poor institutional governance	Political				0				0	Meso	2	4	8	Meso	2	3	6				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1				0	Micro	2	2	4	Micro	2	3	6	Micro	1	2	2				0	Meso	1	1	1
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	2	1	2	Meso	1	1	1	Meso	2	1	2	Meso	1	1	1	Meso	1	3	3	Meso	2	1	2	Meso	1	1	1
Significant public concern	Political	Meso	2	1	2	Meso	2	3	6	Micro	2	2	4	Micro	2	1	2	Micro	1	2	2	Meso	2	2	4	Meso	1	1	1
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2	Meso	2	1	2	Meso	1	1	1	Meso	2	1	2				0
Lack of vocational training of the local workforce	Skills	Meso	2	1	2	Meso	2	2	4	Meso	3	1	3	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	1	2
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	2	2	4	Meso	3	2	6	Meso	2	1	2	Meso	2	1	2	Meso	2	2	4	Meso	2	1	2
Pollution event	Technical	Micro	3	1	3				0	Micro	3	2	6	Micro	3	3	9	Micro	3	1	3	Micro	1	2	2	Micro	2	1	2
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1	Micro	2	1	2	Micro	3	3	9	Micro	3	3	9	Micro	1	2	2	Micro	1	1	1	Micro	2	2	4
Specialist equipment unavailable	Technical	Micro	1	2	2				0	Macro	1	2	2	Meso	2	1	2	Macro	1	2	2	Micro	1	1	1	Macro	2	1	2
Operational failure	Technical	Micro	3	1	3	Micro	2	1	2	Micro	2	4	8	Micro	2	1	2	Micro	1	2	2	Micro	2	1	2	Micro	1	2	2
Infrastructure failure	Technical	Micro	1	1	1	Micro	1	1	1	Micro	1	3	3	Micro	2	1	2	Micro	1	2	2	Micro	1	1	1	Micro	1	3	3

3.4 Risk Location

Where the location of the activity takes place in multiple nations (e.g. extracting a widespread resource) the most important (dominant) location to the case-study is selected as the basis for analysis. The 'Principal Risk Location' identifier shows the location of the data which should be used to make the assessment.

The nature of the risk of 'poor institutional governance' and 'lack of social stability' is that they are omnipresent once the Principal Risk Location is assigned. To avoid double-counting, they are recorded once only. However, the risk is re-evaluated and recorded a second time if a process chain crosses the system boundary i.e. consecutive stages move from having a 'global' location signifier to that of the case-study.

3.5 The Scale of the Risks

An interesting categorisation of the scale of risks to projects was proposed by Bing et al. (2005) and used by Ke et al. (2010). The idea is that the scale is categorised by the origin of the risk in relation to the system boundary. This, it is claimed, can help identify areas or groups of risks that need treatment or monitoring. In particular 'meso' scale risks which Bing *et al*. consider are factors at the project scale, are different in nature to those arising from the relationships between actors involved within the project. We adapt this scheme (Table 10).

Table 10

Definitions for the scale of operation of a risk in fuel supply chains adapted from Bing et al. (2005) and Nakandala et al. (2017).

Scale	Definition for Projects (Bing et al., 2005)	Definition for Food Supply Chains (Nakandala et al., 2017)	Definition for Fuel Supply Chains (Axon, 2019)
Micro	Between agents within projects	Internal to a company	Site specific (company, project)
Meso	Whole-project factors	Supply chain operations beyond the company	National (Governmental)
Macro	Beyond the project system boundary	External to the supply chain	International (widespread or treaty-governed)

The scale of any risk may be different at each stage for any fuel because the technology or activity required may be different. Furthermore, we need to account for entities within and outside the system boundary. The decision of which level is most appropriate should be screened against the 'Principal Risk Location' identifier.

There are different implications depending on whether the micro, meso, macro scale is located as national or global. We suggest that appreciating the differences aids understanding of the risk profile and its dispersion. A more nuanced view of which fuels or parts (or proportions) of the supply chain are influenced by actors of different scales may help shape approaches to policymaking. This is to say that micro and meso scale activities still have meaning in the international (Global) context. For example, governments set policy and regulate businesses – whether they are inside or outside the system boundary – but which stages and risk categories (or individual risks) are affected may change the way R&D programmes are funded perhaps, or may signal the need for negotiation or support for companies operating in that jurisdiction (if Global). The working definitions of the three scales used to guide our assessment for our case study are given in Table 11 and may be characterised as:

<u>Micro:</u> company (or project) level which could include interactions between companies across the system boundary. Within the system boundary communities, regional authorities, or companies could be implementing projects or operating a specific site.

Meso: a national Government has the ability (if it chooses) to regulate or control the activity. Whether this is the Government within the system boundary (the UK Government in the case study) or an exogenous Government depends on the nature of the issue. Some stages or fuels will have a similar issue inside and outside the system boundary. An indicator of this level is a significant number of companies within the system boundary supplying technology and services for that stage of the supply chain of that resource. In a more disaggregated study, the detailed differences between Governments can be drawn out.

Macro: means either that control rests with supra-national organisations or that the market for the fuel source is dispersed internationally. Components of sub-systems are made by international or globalised companies. Projects, sites, or activities require international consortia which may raise finance directly from the international markets.

Table 11
Definitions of scale with respect to the principal risk location.

Scale	Principal Risk Location	
	Global	**Case-study Nation**
Micro	Site or company activity outside the system boundary regardless whether the company from the case-study nation (or elsewhere), is conducting the activity	Site or company activity within the system boundary.
Meso	Government (outside the system boundary) activity or sphere of influence	Government (inside system boundary) activity or sphere of influence
Macro	Activity dispersed internationally or influenced by a supra-national organisation	

3.6 Testing and Operation Methodology

The methodology (Fig. 2) for checking and reviewing the framework and matrix to establish the relative levels between causes of risk in different fuel supply chains (for the case study) has four steps:

1. evaluate one cause of risk across the range of fuels at two stages,
2. select one renewable and one non-renewable fuel to evaluate all sources of risk at the same stage,
3. check the calibration of likelihood and impact levels, scale, and distribution of causes of risk,
4. revisit step 1) and 2) to revise decisions as necessary,
5. revisit and adjust definitions of causes of risk, and level and scale indicators, if required.

The risk of lack of access to capital was selected from Stage 2 (exploit) and Stage 4 (convert) for the first step test. For the second step coal (non-renewable) and off-shore wind (renewable) were checked at stage 2 (exploit). Although this is not a large number to test, the number of individual entries is large enough to obtain consistency of assessment. We checked the relevance of risk causes for those fuel sources which have merged stages e.g. for Wind (offshore), the stages exploit, condition, and convert. For risks which are not relevant to that fuel at that stage, or relevant to that stage at all, the risk scores zero. The merged stages for fuels such as wind are coloured grey; they too score zero. The zero score is justified as reflecting the lower risk associated with co-location of stages.

A key difficulty with such a large matrix is consistency. Each set of risks, levels, and scales was checked against the meanings. Similar fuels were checked against each other to understand why any variation in risk levels and scales occurred. It remains the case that some causes of risks are uncommon. Such situations are assessed on a case-by-case basis and recorded as part of the discussion of the justification for the decision made. The evidence used to support the expert judgements of the likelihood and impact values is a type of meta-analysis in that we are using other studies and their observations (not usually directly articulated as risk) to inform our evaluation.

4 UK Case Study

In the UK case study, the system boundary was chosen as the UK territorial waters surrounding Great Britain and Northern Ireland, together with the land border between Northern Ireland and Eire. In this case study, risks were identified in the supply chains using the seven categories to prompt the search for specific risks. The risk matrix for the UK's national energy system contained commonality of end use mechanisms and shared infrastructure which simplified the analysis, making it more tractable. The evidence base supporting the expert risk assessments was taken from a wide range of published data, interpretation and comment. The 19 generic fuel categories found to be relevant to this case study comprised a group of eight non-renewables (Coal, Demand reduction, Gas, Gas (unconventional), Nuclear (fission), Oil, Thermal (geological), Waste) and 11 renewables: (Biogas, Bioliquid, Biomass (solids), Hydro, Ocean (tidal), Ocean (wave), Solar (electric), Solar (water, thermal), Thermal (low temperature), Wind (offshore), Wind (onshore) (Axon and Darton, in review).

4.1 The Relative Importance of the Causes of Risk

As we have used a consistent set of causes of risk throughout all stages of the supply chain, we can compare how important they are at different stages. There are three possible approaches. The first is that we can calculate a rank order of these risks by summing the individual consequence scores across all fuels. Second, we can count the number of risks which fall into the high-level group. Third, we can examine the pattern of distribution of micro, meso, and macro scale risks as these scales are assigned independently of the likelihood and impact evaluations.

Table 12 shows the ranking according to the total score for each cause of risk across all fuels and stages. We can see that the categories of risks are well-spread through this list. Although the spread is not completely even, this shows that the 34 causes of risk selected represent a range of consequence level. It is likely that these levels will differ from country to country. All seven categories of risk appear in the first 10 places demonstrating that both the selection of risks is appropriate and that important risks are spread widely in their nature.

An unexpected top 10 risk is the lack of specialists in the local workforce. It appears that this may be driven by reported shortages in the electricity distribution industry; the available (grey) literature may suffer from double-counting and over-emphasising this risk. It is not surprising that the lack of access to capital is at the top, since this affects both large and small projects. A residential-scale installation may cost six orders of magnitude less than a power station, say, but it is the cost relative to the income of the buyer which is important. Furthermore, the availability of capital tends to be framed as a go / no go question; this potential to force cessation of an activity places this risk at the highest level.

It is notable that the five causes of risk (Table 12) with the number of high-level individual consequence scores in double figures are all in the top 10 ranks (ranked 1st, 2nd, 3rd, 5th, and 8th); two of these are in the Political category. Apart from the top risks, only 'quality of fuel source' has an appreciable number of high-level individual risk scores. The correlation between the sum of the scores for each cause of risk and the number in the high-level category is reasonable for a large dataset (R^2=0.4488) indicating that the ranking is partly driven by the frequency with which the risks are estimated as high. There are no correlations between the number of risks classed as macro-, meso-, or micro-scale with the total risk score for the causes of risk. This result is expected and confirms that the causes of risk are not defined in a way that introduces any form of bias.

Table 12
UK case study. Rank order of the causes of risk showing the number of risks identified at each different scale, and the number of high-level risks. The risk categories are colour-coded as:

Economic | Environmental | Innovation | Manufacturing | Political | Skills | Technical

Rank	Cause of Risk	Micro	Meso	Macro	H-Level
1	Lack of access to capital	13	25	46	22
2	Changing policy or regulatory framework	0	87	2	10
3	Significant public concern	55	39	0	15
4	Lack of vocational training of the local workforce	0	99	0	0
5	Insufficient capacity to construct sites	42	27	6	16
6	Optimism bias	0	61	32	4
7	Lack of specialists in the local workforce	0	97	0	0
8	Pollution event	82	0	4	10
9	Operational failure	86	10	0	4
10	Natural hazards	87	0	0	3
11	Only marginal improvements likely	0	12	73	0
12	Unable to neutralise waste at decommissioning	81	7	0	6
13	Insufficient capacity to manufacture system components or conversion devices	0	8	79	0
14	R&D capacity or capability does not match the challenge	0	44	40	1
15	Quality of fuel source	44	28	4	6
16	Lack of a well-functioning market	0	22	77	1
17	Lack of public subsidy	0	56	0	3
18	Weak technology transfer environment	0	35	49	0
19	Insufficient rate of improvement in, or lack of enforcement of, standards and codes	0	80	0	0
20	Price volatility	14	12	69	1
21	Lack of material substitutability	0	0	72	0
22	Denial of permission to access sites	58	10	0	1
23	Lack of critical materials availability	0	0	65	0
24	Difficult physical access	57	0	0	2
25	Insufficient rate of infrastructure construction	4	37	0	8
26	Specialist equipment unavailable	19	34	18	0
27	Uncertain decommissioning costs	66	1	0	2
28	Infrastructure failure	42	24	0	0
29	Disputed land rights or resource ownership	50	7	0	0
30	Unable to agree a price for licence or permits	7	30	0	1
31	Lack of basic education levels in the local workforce	0	76	0	0
32	Lack of water availability	23	0	0	0
33	Lack of social stability	0	26	0	2

We note that in comparing the scores for individual causes of risk, renewables score higher than non-renewables in 44% of the assessments. Intuitively this appears high, but the class of renewable technologies does involve some significant risks, perhaps explaining why progress in developing and deploying them is slower than some commentators expected.

Constructing the risk matrix revealed areas for which there is relatively little understanding of the risks to the fuel supply chain, and by extension energy security. These blindspots have received little academic or policy attention in this context. For example, manufacturing receives sporadic concern from Government, but the link to energy security is seldom made. We note that it proved difficult to be consistent with interpreting 'optimism bias' due to the wide range of (uncalibrated) opinions expressed in the literature.

4.2 Systemic risk

Although a detailed analysis of systemic risks is beyond the scope of the current work, we can identify some risks that are common and widespread in the fuel chains examined. It is possible that ubiquitous causes of risk could be systemic, since risk events could occur simultaneously in many fuel supply chains. Using the risk matrix we find that only two causes of risk occur at every stage for all fuels: 'lack of a well-functioning market' (Economic) and 'lack of vocational training in the local workforce' (Skills). If we set an arbitrary cut-off point of a risk appearing in 90% or more fuels (at all stages) then a further seven risks (from five categories) may be considered systemic, and this list is shown in Table 13. The 'lack of vocational training in the local workforce' is highly ranked (Table 12), but the 'lack of a well-functioning market' is ranked mid-table. Furthermore, the other cause of risk with a prevalence higher than its ranking might indicate is 'price volatility' – also in the Economic category. This result suggests that a systemic risk does not have to be of high impact for all fuels, but be present for most.

Table 13
UK case study: potential systemic risks. The most prevalent causes of risk occurring in the risk matrix across all stages for all fuels. The overall rank is that given in Table 12.

Prevalence	Cause of Risk	Risk Category	Overall Rank (of 34)
100%	Lack of vocational training of the local workforce	Skills	4
100%	Lack of a well-functioning market	Economic	16
98%	Lack of specialists in the local workforce	Skills	7
97%	Operational failure	Technical	9
96%	Price volatility	Economic	20
96%	Significant public concern	Political	3
95%	Optimism bias	Innovation	6
91%	Changing policy or regulatory framework	Political	2
90%	Unable to neutralise waste at decommissioning	Technical	12

A further four causes of risk have a prevalence of 89% and this captures the remaining two risk categories (Manufacturing and Environmental). However, there is a clear gap between 'optimism bias' and 'changing policy or regulatory framework' suggesting that only the seven most prevalent causes of risk might have characteristics consistent with being systemic.

4.3 Crossing the System Boundary

Whilst constructing the matrix we recorded the scale of risk and noted whether the principal location of the risk was within or outside the system boundary (the UK territorial border). With respect to the number of risks at each of the three scales of risk we performed a chi-square test to ascertain whether there is any statistical difference between those inside the system boundary (labelled as UK) and outside (labelled as Global) (Table 14). Only stages 1-3 have any risks located outside the system boundary; for stages 1-2 the fuels concerned are Coal, Gas, Nuclear (fission), and Oil, and for Stage 3 only Nuclear (fission).

Table 14
UK case study: chi-square test results for the three risk scales inside and outside the system boundary. This data has two degrees of freedom.

Stage	Scale	Global number	UK number	All Fuels number	Expected Global number	χ^2	p	Statistically significant
1	Micro	35	102	137	35	0.00	0.95	N
	Meso	25	118	143	37	3.72	0.10	Y
	Macro	28	35	63	16	8.67	0.01	Y
2	Micro	48	156	204	48	0.00	0.95	N
	Meso	42	170	212	50	1.16	0.50	N
	Macro	40	100	140	33	1.61	0.50	N
3	Micro	7	78	85	10	0.96	0.50	N
	Meso	13	74	87	10	0.68	0.70	N
	Macro	12	85	97	12	0.02	0.95	N
Total	Micro	90	336	426	91	0.02	0.95	N
	Meso	80	362	442	95	2.26	0.30	N
	Macro	80	220	300	64	3.88	0.10	Y

The chi-square test shows that mostly there is no statistical difference between the prevalence of each scale inside and outside the system boundary. However, there are two marginal cases, namely at Stage 1 (Meso) and the Total (Macro). There is one clearly significant case which is Stage 1 (Macro), showing that risks located outside the system boundary attract more macro-scale risks than expected. This can be interpreted as: the fuels which the UK uses have causes of risk for exploration more frequently subject to global pressures and markets. A possible explanation for this is that the fossil fuel industry is distributed globally but at low density, and requires very large levels of investment to create a viable project. This is not altogether surprising. What is more curious is that the meso-scale causes of risk (Government level) were not clearly different inside and outside the boundary. Given that many sources of fossil and nuclear fuels are located in countries with poor governance records we might expect that meso-scale risks would be more severe outside the UK's border, but this is not observed in our data.

5 Expert Verification Workshop

In work requiring expert judgments, verification is an important stage. Usually, the approach is to convene a stakeholder consultation or workshop to test methods or outcomes, or to gather specific input (Johansen and Rausand, 2014). Seeking stakeholder input is an important part of the Process Analysis Method (Darton, 2017). The exact approach will depend on time available, scale of the project, maturity of the topic or method, or the type of information being sought (Chang et al., 2014; Eskandari Torbaghan et al., 2015).

To test the results of our novel approach and assessment we convened a panel of experts to elicit opinions and implicit knowledge not commonly put into the public domain. The aim was to uncover why industry experts consider something to be important. Inevitably, statistics and the literature offer only part of the landscape for a research area such as energy security. Academic studies may model sets of restricted or closely defined circumstances (scenarios) but cannot properly incorporate the professional experience of experts. Dagonneau et al. (2017) observed from their national-scale environmental policy workshops that compared with the literature, experts gave a narrower range for impact severity for environmental risks, a higher median severity for economic risks, and a wider spread of severity impact scores for societal risks. The UK energy industry is mostly in the private sector, but as a public utility it is strongly regulated with significant policy and legislative guidance. Therefore the interface between government and industry is interesting and pertinent to understanding how different sets of sector experts view the relevant risks, and any risk evaluation should reflect the common understanding of the stakeholders (Duijm, 2015).

5.1 Workshop objectives

Our aim for the event was to consider the relative importance of causes of risk for a subset of fuels, and to suggest how policymakers can account better for risks when developing energy policy. We opted to hold a 2½ hour workshop in London with 15-18 participants. Although this number could not cover all possible combinations of technology or job function, we considered that it was a realistic number which would cover the main areas. As the literature on which we had relied was predominantly academic, we chose to invite mostly those with relevant private sector experience of ten or more years. Invitees were chosen to reflect the categories of risk and/or process stages. We made 38 invitations of which 19 were accepted (four were substitutes suggested by the invitee). A further five people were unavailable and unable to offer a suitable substitute. Sometime after the invitations had been made, the UK Prime Minister announced a general election which placed the civil service into purdah. Although this legally only prevents policy announcements from being made, government departments withdraw from even attending events as observers. This brought the final number of participants down to 16; one person did not attend on the day. We agreed to maintain the anonymity of the participants, but Table B.1 gives a breakdown of their expertise in relation to our categories of risk and stages. All discussion was under the Chatham House rule[1].

The fuels for discussion were selected using the following criteria: 1) having importance in the current energy system, or 2) considered as having priority in future energy systems, or 3) showing interesting properties in our initial analysis. If the attendee group had lacked knowledge of any of the fuels we would have withdrawn that fuel from discussion. The final list of fuels for discussion was: bioliquids, demand reduction, gas (unconventional), nuclear (fission), ocean (tidal), oil, solar (electric), and wind (offshore).

Participants were assigned to one of three groups, each with a facilitator. Groups were formed based on specialist fuel knowledge and each group discussed three fuels. Membership of the groups (and facilitator) were kept constant. Although we had working definitions of the causes of risk, to give flexibility participants were allowed to interpret these. Any deviations were recorded and explained. Participants were sent briefing notes on the project, the definitions of fuels, risks, and categories. All notes were written by the facilitators. We chose not to use audio recording devices as this can inhibit free exchange of views. There were three tasks as follows:

Task 1: Each group was to identify the most and least important causes of risk in each category for each fuel. The key point was to extract the reasoning why each expert had come to that conclusion. The discussion of differences in opinion was also important to record. Facilitators were instructed that if that proved too contentious or difficult then to prioritise the stages with which the group was most confident, though this did not prove necessary.

Task 2: In open session with all groups together, participants compared and contrasted these and prioritised the causes of risk across all eight fuels.

Task 3: Also in open session, participants discussed what policy measures or instruments BEIS (or other Government dept) could enact to mitigate the most important risks occurring. Originally this was to have input from the departmental representatives giving useful direct

[1] Participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed.

feedback as part of the discussion. Without the departmental representatives present this task was somewhat muted, but opinions were noted.

The open session also enabled facilitators to check whether a strong opinion was common or pertained only to an individual. We explicitly asked for criticism of our method of assessing risk in the open session.

5.2 Summary of Workshop Discussions and Conclusions

Each of the three groups discussed a set fuels, with the free-form discussion allowing evidence and their direct experience to illustrate risks as they encountered and dealt with them. The complete discussion and set of notes are given in Axon (2019); we summarise the key points as follows.

In discussing solar (electric) and demand reduction Group 1 noted that one of the key risks is the changing policy or regulatory framework. For solar PV, the feed-in tariff was highlighted as an example. The main risk raised was that the notional discount rate of the future value of Demand Reduction is considered aggressive meaning that its long-term value is not recognised, thus not worth investing in. The risk of rebound effects was considered high. The value of Demand Reduction is underplayed generally. Generally, the lack of access to capital was considered to be important.

Group two discussed unconventional gas, nuclear fission, and tidal energy. The system and processes themselves have effects which need to be discerned; the risk is failing to integrate "*enough*". The context could be political, technical, or innovation. Optimism bias was considered to be a more significant risk than usually perceived. A general comment about political risk was that the interconnections (physical infrastructure and commercial) are on the rise in the energy sector. However, this tension, in part created by globalisation, is with energy independence.

The greatest concern noted by the third group (oil, offshore wind, bioliquids) was the changing of the policy landscape, described as "*policy and regulatory meddling*" leading to a risk premium in the market price. Misconceptions drive policy and behaviour and is incompatible with stable future climate policy. Also noted as important was the innovation category, in particular the transition to EVs, and it was noted that there may be a slowing innovation optimism. The Skills category was thought to be of the least concern. In oil and gas, for example, it was thought that there was an oversupply of skilled people.

During the open discussion session, the participants agreed that a changing policy or regulatory framework was the most significant risk across all fuels and process stages. They commented that it was one which the UK Government should treat with urgency and the highest priority (within BEIS, the UK ministry currently responsible for energy and industrial strategy). The participants agreed on a further seven risks which they considered to be more important than others, but not as significant as a changing policy or regulatory framework (Table 15). The assessment made (Table 15) corroborates our analysis (Table 12).

Table 15

Summary of the risks identified as most significant by the workshop participants.

Cause of Risk (unordered)	Risk Category
Changing policy or regulatory framework	Political
Lack of access to capital	Economic
Insufficient rate of infrastructure construction	Manufacturing
Optimism bias	Innovation
Significant public concern	Political
Lack of a well-functioning market	Economic
Lack of public subsidy	Innovation
Uncertain decommissioning costs	Economic

The participants made three suggestions for discussion with the Department for Business, Energy, and Industrial Strategy. In no particular order:

1. Funding calls: the use of exploratory projects is the wrong approach because the public pays the development risk of the energy sector. This was considered as a form of privatising the profit whilst subsidising the risk.
2. BEIS should be more conscious of, or explicit about acknowledging, optimism bias.
3. Attempting to set up an open market is not working. The context for all energy policy is the supply-demand balance. Yet the simple use of £/MWh does not lead to a balance across the whole energy system because it is a poor metric for incorporating the requirements for flexibility and for multiple energy vectors. This means that a basket of relevant indicators is required to formulate, set, and judge policy instruments. It would be best not to use cost minimisation as a mechanism (or as a modelling tool).

One participant noted that the problem with energy security, and energy issues in general, is that common perceptions are often very far from the truth. The participants noted two criticisms of our methodology. The first that systemic risks are not being considered, only individual fuels. The second is that it appears to be about analysing the existing system – things as they are or are easily changed. Incorporating the risks goes some way to tackle this, but another participant thought that it is not a predictive tool as such. However, trends in data can be observed and used, though exogenous shocks cannot be accounted for without scenario analysis. Another question raised was how to account for risk interactions.

6 Conclusions

Understanding energy security requires knowledge of relevant risks and their origin. We have shown that it is feasible to generate a risk matrix relevant to national energy security using a transparent methodology to analyse the energy system at an appropriate level of granularity. The method quantifies risks in fuel supply chains by rating their likelihood and impact, thereby avoiding the arbitrariness in selection and weighting of relevant characteristics that has been frequently employed and criticised in the literature. The location and scale of the causes of risk are pinpointed, facilitating potential mitigation. The completed risk matrix comprises several thousand value judgements, supported by literature and a stakeholder consultation, but naturally involve a degree of subjectivity. However, using a defined framework and common understanding of risk across different fuels promotes self-consistency. This was checked statistically for our UK case study, and no systematic bias was found. We have shown that the overall assessment of risk for each fuel has low sensitivity to uncertainty in the scores for likelihood and impact for individual causes of risk.

The 34 generic causes of risk identified in UK case study are likely similar for other developed (and many developing) economies. However, risk scores depend on national circumstances, particularly resilience of the system, and may be expected to vary between countries. For the UK, the three most important causes of risk were found to be 'lack of access to capital', 'changing policy or regulatory framework' and 'significant public concern' (which implies risk from public protest). These causes had a large number of individual risks ranked at a high consequence level and were amongst those identified as most significant by participants in the expert verification workshop. All seven categories of risk include individual risks of high consequence, so no category should be neglected when assessing energy security. Seven causes of risk, led by 'lack of vocational training of the local workforce' and 'lack of a well-functioning market' occurred for all, or nearly all, fuels for all stages in the supply chains. We suggest that these risks may be considered systemic, as risk events could occur simultaneously for many fuels. We consider this is an important area for future research.

The scale of each risk was assigned as either micro (site), meso (national) or macro (international). For fuels involving international operations there was little statistical difference between the prevalence of risks at home and abroad, except at the exploration stage. This stage attracted more macro-scale risks than expected, a result of exploration risks for fossil fuels and nuclear fission. We note that in the overall ranking of causes of risk, the top scorers tended not to have many macro risks, contrary to much popular opinion that sees international supply chains as inherently more risky. We conclude that a rational policy on energy security would give priority to mitigating risks at a local or national scale.

We note three limitations of our method. First, its comprehensive nature as an in-depth study means that it is a time-consuming exercise. However, once completed for a particular use case, periodic updating should only require a modest amount of additional work. Secondly, the method is designed to analyse an existing system – as it is or has been structured historically. No modelling of dynamic change is built in. However, we note that most causes of risk only change slowly or incrementally, a limitation further mitigated by the 'pricing in' of potential shocks (the method incorporates the maximum impact of each risk event). Thirdly, as remarked by participants at the expert workshop, by considering risks independently in separate supply chains, the method does not account adequately for systemic risk. We tentatively identified some systemic risks in our results (section 4.2). Researchers adopting our method and adapting it to different case studies will create refinements and perhaps discover developments and simplifications. Complex methodologies improve with both the number and diversity of use cases.

We observe that the literature on energy security has been uneven in its attention, focussing particularly on certain risks and certain fuels (predominantly fossil). There is an urgent need for more research on the causes of risks associated with manufacturing, innovation and other aspects of the transition to renewables. Research is also needed on the risks involved in policies and technologies for demand reduction to provide insight to this vital aspect of meeting the supply-demand balance. Studies providing evidence for risk scores for fuel supply chains in more countries would help underpin all assessments of energy security and highlight local, national as well as global issues. Another issue requiring research is developing the *risk matrix* (described in this work) into a *risk register* for energy security, in which consequences and responses to risk events are addressed. There is an urgent need for greater stakeholder consultation on the nature and location of risks in fuel supply chains. Our pilot-scale workshop demonstrated the importance of such input.

Though developed as an approach to energy security, the methodology could be used to assess the risk in other supply chains that service an economy, for example, water and food. The key point is that the assignment of supply chain stages is flexible, as is the selection of causes of risk – both can be chosen for the system under review.

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Appendix A. Error propagation and uncertainty estimation in the risk scores

In devising a method to reach a composite score which is fully representative of the overall risk several characteristics of the whole fuel supply chain need to be taken into account, namely:

- five fuels branch at different stages into pathways which produce different energy vectors (Biogas, Biomass, Gas, Gas (unconventional), and Thermal (geological)),
- the 19 fuels share only five different distribution systems (electricity networks, road tankers, and pipeline for gas, oil, and water), and
- four different end-use types.

It is not reasonable to attribute the full risk score to every fuel, indeed this would be a form of double-counting. Furthermore, shared infrastructure and end-use type suggests that using a new fuel which produces an existing energy vector presents only a marginal increase in risk (and cost) for its introduction. It is a separate matter whether this reduces system resilience.

Stages 1-4 are independent for each fuel thus can be simply summed for each fuel. At stage 4 the branching points score zero. We assume that the risk for end-use type (stage 6) is shared equitably, but there are some minor deviations for some distribution systems (stage 5), e.g. the offshore network portion for marine and wind technologies. These fuels then share the onshore electricity networks with other fuels. We assume that the common elements are shared, but we need to account for the unique risk associated with some fuels over and above that of the common elements. The total (composite) total risk score (TRS) for a fuel *f* can be expressed as (Axon, 2019)

$$TRS_f = \sum_{i=1}^{4} S_i + \sum_{j=1}^{m}\left[\left(S_{5,j} - U_j\right) + \frac{U_j}{m_j}\right] + \sum_{k=1}^{n} \frac{S_{6,k}}{n_k} \quad (1)$$

where:

S_i = sum of the risk score for the *i*th stage,

U_j = risk score of the underlying distribution *j*th infrastructure type,

m_j = number of fuels sharing the *j*th infrastructure type,

n_k = number of fuels sharing the *k*th use type.

This approach accounts for the marginal risk element of shared infrastructure. This also explains why introducing a fuel (or new use of an existing fuel) difficult when it requires a new dedicated distribution mechanism.

Although the precise ranking of different fuels is not important for energy security policy discussions, broad groupings may be instructive. In any multi-step calculation it is possible to estimate the compound error (Hughes and Hase, 2010; Squires, 2008). Estimating the uncertainty in the final risk total gives a handle on whether and by how much the spread in risk scores overlap for different fuels. Uncertainty arises from incorrect estimates of the likelihood or impact of a cause of risk. As it is likely that the broad level of the risk (low, moderate, high) will be estimated correctly, the error in any individual risk score (likelihood x impact) is most probably ± 1 and at worst ± 2 (termed uncertainty in the risk, ΔR). It is more intuitive to use the raw risk score rather than the normalised score as it keeps the uncertainty in the risk (ΔR) in native units. An uncertainty analysis serves two purposes 1) to see which fuels have statistically significant similar scores, and 2) to gain understanding of whether reappraisal of the likelihood and impact scores in future analysis will significantly affect the ranking.

In Eq. 1 n_k, m_j, *and* U in the elements for stages five and six are constants which have no uncertainty, therefore Eq. 1 is of the form

$$TRS_f = S_1 + S_2 + S_3 + S_4 + S_{5,i} + S_{5,j} + S_{6,i} + S_{6,j} \quad (2)$$

where *S* is the sum at each stage. The general form of the uncertainty for a sum is

$$(\Delta Z)^2 = (\Delta A)^2 + (\Delta B)^2 \tag{3}$$

Thus, the uncertainty in the composite risk score can be expressed as

$$\left(\Delta TRS_f\right)^2 = (\Delta S_1)^2 + (\Delta S_2)^2 + (\Delta S_3)^2 + (\Delta S_4)^2 + \sum_{j=1}^{n}\left(\Delta S_{5,j}\right)^2 + \sum_{k=1}^{n}\left(\Delta S_{6,k}\right)^2 \tag{4}$$

But as ΔR is an integer we can state that

$$(\Delta S_i)^2 = \sum_{p=1}^{N}\left(\Delta R_p\right)^2 = (\Delta R_1)^2 + (\Delta R_2)^2 + \cdots + (\Delta R_N)^2 \tag{5}$$

where N = number of relevant (non-zero) risks at the *ith* stage. If we take ΔR=1, then

$$(\Delta S_i)^2 = (1^2 + 1^2 + \cdots + 1^2 +)_N = N$$
$$\Delta S_i = \sqrt{N} \tag{6}$$

Therefore, the uncertainty in the composite risk score for any fuel f (Eq. 4) is:

$$\left(\Delta TRS_f\right)^2 = \sum_{i=1}^{4}\left(\sqrt{N_i}\right)^2 + \sum_{j=1}^{p}\left(\sqrt{N_{5,j}}\right)^2 + \sum_{k=1}^{q}\left(\sqrt{N_{6,k}}\right)^2$$

$$\Delta TRS_f = \left[\sum_{i=1}^{4} N_i + \sum_{j=1}^{p} N_{5,j} + \sum_{k=1}^{q} N_{6,k}\right]^{1/2} \tag{7}$$

Eq. 7 can be described as the uncertainty in the total risk score for a fuel is the square root of the sum of the number of relevant (non-zero) risks for that fuel. Similarly, if the error ΔR=2 on each risk then the uncertainty is multiplied by √2.

From this analysis, we suggest that the groupings (Table A.1) are unlikely to switch membership without radical changes in at least several categories of causes of risk. Thermal (geological) is difficult to attribute as it is located equidistant from two groups, but for convenience we make it part of the Biomass group. The lack of overlap using the worst-case uncertainty implies that the risk scores we have calculated are sufficiently robust to project, using sets of scenarios into the medium-term – 20 years hence, say. There is evidence from the slow-moving nature of national economies that 20 years is a reasonable time-constant (Roberts et al., 2016).

Table A.1
UK case study. Cluster memberships which are unlikely to switch, though the ranking of individual fuels may change over the medium-term.

Group Members	Average Normalised Risk Score (a.u.)
Gas, Gas (unconventional), Oil, Nuclear (fission)	97
Biogas, Biomass, Coal, Thermal (geological)	68
Bioliquids, Demand Reduction, Ocean (tidal), Ocean (wave), Waste	45
Hydro, Thermal (low temperature), Wind (offshore), Wind (onshore)	33
Solar (electric), Solar (thermal, water)	23

Appendix B Workshop Participants

Table B.1
Characteristics of the workshop participants.

Job Title	Expertise	Stage(s)	Main Risk Categories
Partner	Investment	3, 4, 5	Economic
Consultant	Oil	1-5	Environmental
Manager	Nuclear fission	1-4	Innovation
Consultant	Renewables, investment	2-5	Manu, innovation
Researcher (academic)	Public acceptability	1-6	Political
Chief Executive	Demand	6	Political
Manager	Markets	1, 2	Economic
Senior Engineer	Nuclear fission	3, 4	Technical
Research Fellow	Demand	5	Environmental
Deputy Director	Shale gas	1, 2, 3	Economic
Director	Infrastructure	4, 5	Technical
Policy Analyst	Coal and renewables	4	Political
Research Fellow	Investment	3-6	Technical
Senior Lecturer	Heat	5, 6	Political
Advisor	Gas	2-4	Political
Company Director	Markets, investment	3-6	Economic