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Measuring risk in fuel supply chains

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Abstract

In assessing energy security, risk is recognised as being important. However, it is rarely assessed in a transparent quantitative way. To address this, we decompose the global energy system into 27 generic fuel supply chains and six sequential process stages. One of these fuels – 'Demand Reduction' – is conceived as 'negative fuel' to satisfy the supply/demand balance. We use 7 categories of risk and estimate the likelihood and impact for each cause of risk for each fuel and each process stage – demonstrating the tractability of creating a risk matrix for the whole energy system. Impacts of risk events are evaluated using the triple-bottom-line methodology, allowing for system resilience. This direct assessment of risk events is based on published data, interpretation and comment (with risk seldom directly articulated), and eliminates the need for arbitrary weighting of individual risks in the overall assessment. In a UK case study, 19 of the fuel categories were found to be relevant and those with the highest overall risk were a group of fossil fuels and nuclear fission. The least risky fuels were renewables, including solar (electric and thermal), wind, and hydro sources. Cost reduction alone was shown to be insufficient to deliver an efficient and more environmentally benign energy system. The UK case study demonstrates the need for governments to consider more closely policy relating to long-term energy security and identifies key elements of risk hindering the low-carbon transition.

1 Introduction and Background

To ensure their energy security, nations commonly require diverse sources of primary energy and fuel products which are provided through supply chains of various lengths and complexity. Few such supply chains will be completely within the borders of a single country, even if the fuel source is indigenous: detailed analysis may reveal that necessary equipment, processing plant, or skilled labour for example must be resourced beyond the national boundary. But whether wholly within a nation's borders or not, all activities in supply chains carry risks of some sort, and mitigating these risks is key to the energy security of a country (Jansen et al., 2004; Chester, 2010; Axon and Darton, 2021a). Understanding energy security, and devising policy to maintain it, has become increasingly important in recent years against the background of rising global energy demand yet widespread concerns about nuclear power and the environmental impacts of fossil fuels.

Despite this importance and growing topicality Kucharski and Unesaki (2015) say of the conceptual models proposed for evaluating energy security "*there are few examples of models that clearly define the broad range of risks faced by contemporary, complex energy systems*", most models being restricted to consideration of the effect of supply disruption. Månsson *et al*. (2014), in a review of assessment methodologies identified the need for better understanding of how sources of insecurity develop and how the energy system can adapt to reduce vulnerability. The importance of the timescale of reference was underlined by Cox (2018): *"…a differentiation between gradual 'stresses', such as climate change or geopolitical tensions, and sudden 'shocks', such as a technical fault at a plant or a powerline failure."* Assessment of energy security requires consideration of all sources of insecurity, but as Cox points out, assessments rooted in social sciences and international relations tend to focus on longer-term dynamics, whereas shorter-term dynamics tend to dominate analysis in the physical sciences and engineering literature. Assessments of energy security thus tend to represent the background and interests of those making them, or as Cherp and Jewell (2011) remark *"Unfortunately, the method of including or excluding issues into the scope of energy security studies is rarely transparent or rigorous."*

We define energy security as the low-risk (dependable) meeting of needs for energy within an economy (Axon and Darton, 2021a). Energy (in)security is a result of the wide range of risks and threats to which the energy economy is exposed. Quantifying energy security is a complex task which can be conveniently tackled by identifying the key characteristics of the system and measuring them to produce a set of indicators representing the energy security of the country examined. The objective of a rigorous and transparent method of assessing energy security is to provide stakeholders with a credible summary of the state of a nation's energy economy. It should if possible enable the screening of future scenarios, and assist decisions about investment, policy, international links, and so on.

To quantify risks and their consequences, we use the well-known risk matrix method for assessing risk severity (Gardoni and Murphy, 2014; Thomas et al., 2014). We incorporate this within a framework for screening the country's system for energy supply and utilisation. Within the assessment framework, elements of the system such as competing technologies, geographical sources of fuels, environmental constraints, technical limits, and societal factors must be described and their effects accounted for in a relatively disaggregated manner, considering both national and international interactions. We identify risks by examining the fuel supply chains and treating the technologies which exploit these fuels as subsidiary. A key feature of the approach is that the severity of all risk impacts is quantified using the same scale, accounting for resilience of the energy system. This eliminates the need to introduce a weighting scheme when comparing or aggregating the contributions of various risks, which often involves arbitrary or non-transparent factors (Gasser, 2020).

The objective is to design a framework that is methodical and transparent; that is, an observer should be able to trace the reason for the selection of any indicator or its metric (value), and thus modify the analysis for different circumstances, or to incorporate other judgements. The methodology needs to be independent of any nation or source of fuel though inevitably a country-assessment will take account of opportunities or limitations presented by geography, specific political matters, or the economic state (level) for example. Note that we are attempting to assess the risks associated with particular fuel types within the national energy system and are not assessing the risks of any individual project. The application to a nation – the case study – will test the method and illustrate its potential use.

1.1 Sustainability assessment: the Process Analysis Method

Energy security and sustainability are concepts that have much in common (Axon and Darton, 2021a). Both concepts target desirable ways of managing the resources of an economy, in the one case to deliver energy security, and in the other to deliver sustainability. Further, if energy security is to be assured for future generations, then it seems necessary that energy supply and use must become sustainable, like the use of all resources.

The Process Analysis Method (PAM) fits the requirements for a methodical and transparent framework suitable for screening a national energy system in a relatively disaggregated manner. The PAM was developed for the sustainability assessment of a palm oil production facility (Chee Tahir and Darton, 2010) and subsequently applied to the UK car fleet (Smith *et al*., 2013), technologies for removing arsenic from drinking water (Etmannski and Darton, 2014), river basins (Wu *et al*., 2015), bioprocessing (Sanchez *et al*., 2016), urban water security (Jensen and Wu, 2018) and extended to assess network processes (Neumüller *et al*., 2015) and civil construction projects (Tetteh *et al*., 2019). The PAM examines how processes cause impacts which enhance or diminish the three stores of capital (environmental, human/social and economic), and is thus a triple-bottom-line assessment. The impacts cause observable issues for the recipient stakeholders which are measured by indicators and their metrics. In this way, the PAM is data-driven, transparent, robust, and repeatable. Darton (2017) details how to implement the PAM for a system of interest, but we summarise the seven steps:

1. Give a clear high-level view of the processes which comprise the system.
2. Define the system boundary.
3. Define what is a desirable outcome in the context of the system.
4. Define the 'perspectives' – yardsticks by which to judge whether the change in an indicator moves the system towards or away from the desirable outcome.
5. Identify broad groups representing the impact generators and receivers (the stakeholders).
6. Identify impacts, with candidate indicators and their metrics.
7. Check the indicators against the definition of the desirable outcome, and that each has a complete chain linking process to indicator.

When using the PAM to assess energy security (as opposed to sustainability), the desirable outcome of step 3 is the state of perfect energy security. This is a state in which risk events either have a very low probability of occurring, and/or risk events have a very small impact on the three stores of value. The severity of risks is assessed using the risk matrix approach.

It might be argued that the first step of this suggested methodology, making an inventory of all the processes involved in the energy system of an entire country, is too complex to be undertaken, and perhaps unnecessary. There are however mitigating factors:

(a) A national energy system can be split into component parts, some of which are common to different fuel types. For example, both natural gas and wind farms generate electricity that is distributed by a grid network to users. Other types of replication also occur in the analysis – for example we observe that industrial-scale developments of whatever type, can provoke societal objections and thus involve a risk related to project planning. Treating such risk factors in a similar way across the whole system both promotes self-consistency and reduces workload.

(b) Treating similar elements of the system consistently also enables judgements to be made quickly about which impacts and risks can be safely ignored, as being below a certain threshold of significance.

(c) A certain "granularity" is acceptable in the analysis. This means that processes can be bundled if the result is a meaningful aggregation in terms of its risks and impacts.
(d) Splitting the energy system into component parts is required for the analysis, but the PAM does not require numerical modelling. It is sufficient that risks and impacts can be estimated and ranked, but high precision is not expected or needed. Key parts of the analysis could of course be backed up by more rigorous modelling, if necessary.

The necessity for thorough study of the operation of the energy system is a result of the twin objectives of completeness and transparency - that the indicators of energy security should include all relevant and significant factors, selected using a method that can easily be reported, scrutinised and adjusted.

1.2 Risk registers and quantitative assessments

When using an approach based on the PAM for assessing energy security it is necessary to deal with risk, incorporating steps that are not required in a sustainability assessment. These steps can use risk analysis techniques that are well established in various applications. Maintaining an inventory of risks, adverse events that might occur, is a matter of good institutional governance, and such an inventory is commonly known as a 'risk register'. According to Willams (1994), writing in the context of projects, a risk register has two roles, as *"a repository of a corpus of knowledge"* and as a basis to *"…initiate the analysis [of risks] and plans that flow from it"*. Many nations keep a risk register, often related to physical security (Hagmann and Cavelty, 2012). The UK risk register (Cabinet Office, 2017) also incorporates emergencies such as severe nuclear power plant accidents, maritime disasters, infectious disease outbreaks, cyber-attacks, and civil unrest. In his analysis of the British and Dutch national risk registers Vlek (2013) identifies many weaknesses in the methodologies behind the construction of these important national planning documents, and suggests using a broader concept of risk which he defines as "*…an insufficient potential to meet external harmful demands*"; this definition introduces an element of the ability to cope with the risk event. Aven and Cox (2016) bluntly suggest that (inter)national assessments need to incorporate risk analysis techniques to be more effective.

The risk matrix is a simple analytical tool widely used in risk assessments, where each specific risk is assessed according to the likelihood of the risk event occurring, and the magnitude of the impact if it does. The level of risk is usually evaluated as the product of probability of occurrence and the consequence of the outcome of the risk materialising (Gardoni and Murphy, 2014). The risk matrix enables risks to be assessed and ranked, even though it may be difficult to estimate accurately either the likelihood or the impact, or both. This approach, if used within a systematic method of screening its operations, provides an organisation with a technique for identifying its most serious risks, and is thus well-suited to the assessment of energy security.

Quantitative risk matrices are widely used because they are perceived as easy to construct, explain, and score (Thomas *et al.*, 2014), for example in electricity generation (Hammond and Waldron, 2008), future (smart) electricity networks (Rossebø *et al.*, 2017), human health (Schleier and Peterson, 2010; Vatanpour *et al.*, 2015), pipelines (Henselwood and Phillips, 2006), process safety (Whipple and Pitblado, 2010), project management (Hillson and Simon, 2007), shipping (Hsu et al., 2017; Marchenko et al., 2018), agricultural pollution (Hewett *et al.*, 2004), and water recycling (West *et al.*, 2016). Several organisations give guidelines for using risk matrices in their sectors (NPSA, 2008; IMO, 2013; IPIECA and IOGP, 2013).

Despite their popularity, quantitative risk matrices exhibit some drawbacks, though with careful design for a specific task, these can be mitigated. Hitherto identified drawbacks are spurious resolution i.e. lacking granularity (Cox, 2008; Smith *et al.*, 2009), they cannot measure aggregated total risk for a process where the risk scores have units (Baybutt, 2016), they cannot account for correlated risks (Hubbard and Evans, 2010; Baybutt, 2016), can be subject to cognitive bias (Smith *et al.*, 2009; Hubbard and Evans, 2010), mathematical inconsistency (Cox, 2008; Hubbard and Evans, 2010; Thomas *et al.*, 2014), potential for ranking reversal errors (Baybutt, 2016), and range compression (Cox, 2008;

Ni *et al*., 2010; Levine, 2012). To deal with flaws, Cox (2008), Levine (2012), and Baybutt (2016) recommend logarithmic scales to increase the dynamic range of values. Smith *et al*. (2009) counteract cognitive bias by applying statistical tests such as maximum likelihood estimation, and Duijm (2015) suggests using probability-consequence diagrams with continuous scales. Despite the shortcomings, Duijm (2015) concludes that risk matrices "...offer support in cases where explicit quantification cannot be agreed upon."

It is particularly important to use the risk matrix in an appropriate manner. Baybutt (2016) and Peace (2017) remark on the dangers of poorly designed risk matrices for security (as opposed to the more familiar safety) in the process industries. Bao *et al*. (2018) conclude that the technique is useful for assessing risks in vague environments as it is effective when data are not sufficient for purely quantitative tools. More generally, MacKenzie (2014) addresses the challenge of communicating complex risk information to the public, and Johansen and Rausand (2014) suggest using deliberation, incorporating stakeholder views and other information, as part of risk-informed decision-making. There are advances suggesting applicability to energy security: for example Fernandes *et al.* (2010) suggest using risk matrices within a (hierarchical) framework for identifying risk in the petroleum supply chain, and Goerlandt and Reniers (2016) advocate visualisation techniques with the risk matrix method to tackle uncertainty and the 'strength of evidence'. Aven (2017) presents practical methods for dealing with the recurring issue of uncertainty, using the 'strength of knowledge' where subjective judgments need to be made in the absence of sufficient data.

2 The risk assessment framework

Our approach is to identify the set of fuels that comprise a nation's energy economy and disaggregate the activities which make up the supply chains into an appropriate number of stages. For each stage, we review the activities occurring and the possibility that they might be perturbed in some way. These possible perturbations are the risks identified for each fuel at each stage, which build up to form the risk matrix. The purpose of the risk matrix is to record the structure of the fuel supply system as we analyse it, and to identify the location and severity of all the significant risks. The risk matrix contains the results of our analysis which must be validated where possible and communicated.

When setting up the framework for the risk assessment of a system with a defined boundary (Fig. 1), there are five steps. First, we identified a set of classes of fuel sources and defined their characteristics. Second, we exploited the PAM methodology to identify and define the process stages at an appropriate level of disaggregation. The level of aggregation chosen depends on the purpose of the study. Then, from a review of literature and expert input we, third, identified and defined seven categories of risk, and, fourth, the causes of risks. Fifth, we constructed and tested the risk matrix to evaluate the performance of the interacting elements of the framework. In practice there are feedback loops as indicated in Fig. 1 to settle on a workable structure for the fuel supply chain system and a manageable list of causes of risk.

Finally, once the assessment framework was completed, the assessment for the UK case study was conducted to populate the risk matrix with the likelihood, level of impact, and consequences of each cause of risk. Populating the risk matrix with the appropriate values was the principal and most time-consuming step in the assessment exercise. Analysis was conducted to screen for various patterns of risk distribution between stages, fuels, and other relevant features.

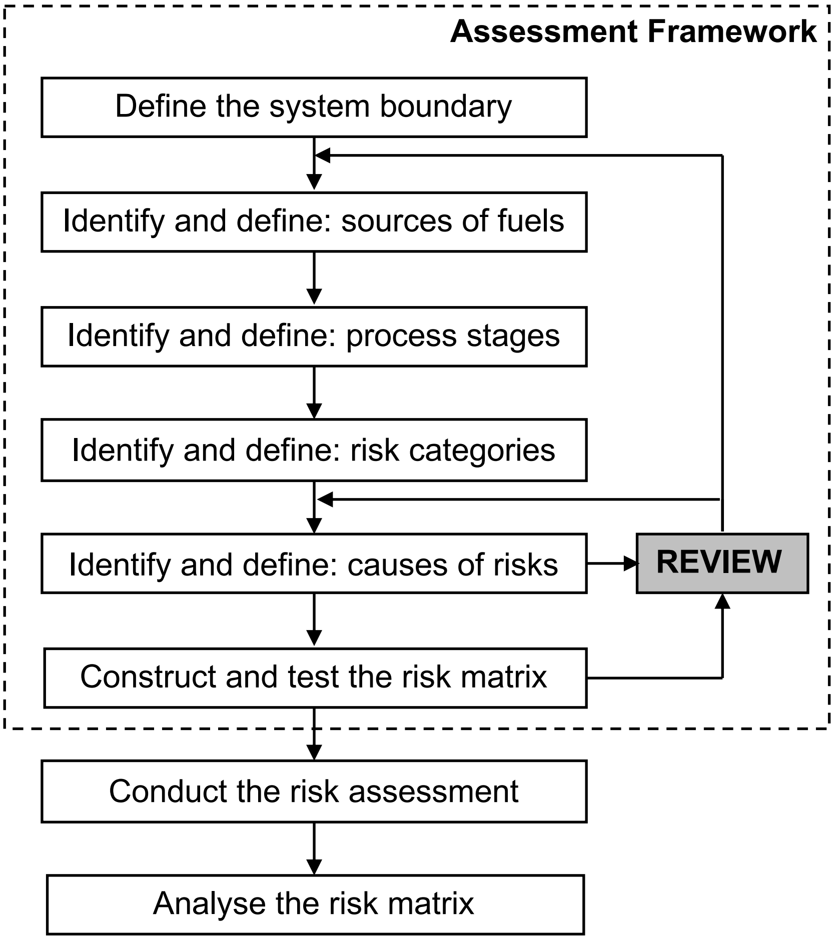


Fig. 1. The steps taken (with feedback) to generate the assessment framework.

Subsequent assessments only need check that the list of fuel sources is correct for the particular study. There will be merit in testing the method with one fuel or cause of risk to gain familiarity with the method, but in most cases researchers will be able to proceed to conducting the risk assessment. Assuming access to sufficient levels and variety of expertise, the size of the team available determines the scope of the assessment exercise, and pace at which it proceeds.

2.1 Raw fuel sources

We identify 27 fuel categories which encapsulate likely future variants (Table 1) in some cases these categories represent a family of sources. Useful definitions and discussion of ‘conventional’ and ‘unconventional’ fuels are given by Rogner *et al*. (2012).

Table 1
The set of generic fuel categories. Each country-based study need only use a subset of relevant fuel sources.

Fuel Category	**Notes**
Biogas	*Renewable*. Methane from biogenic sources like sewage, livestock and agricultural waste. Used in direct combustion or injected into gas network. In some cases production method is similar to bioliquids. Anaerobic Digestion (AD) is a common route, the fuel being waste and renewable c.f. Gas (unconventional). Category includes off-gas from landfill sites.
Bioliquid	*Renewable*. Similar production methods to biogas and biomass, but bioliquid manufacturing is likely to be a unified facility. Bioliquids also produced from upgrading gases or as by-products from biomass processing. Mostly for transport fuels; products include methanol, ethanol, biodiesel.
Biomass (solids)	*Renewable*. For direct combustion alone or co-fired with coal. Mainly crop residues, short-rotation coppice, aquatic biomass.
Coal	*Non-renewable*. Includes hard and soft (brown/lignite) but excludes peat.
Demand reduction	*Non-renewable*. Conceived as 'negative fuel', negafuel, with two main elements: improved energy efficiency through devices, and change in behaviour by people.
Exotic gases and liquids	*Non-renewable*. Currently liquid nitrogen, ammonia, hydrogen, and carbon dioxide (capture and use).
Gas	*Non-renewable*. Gas conventionally extracted. Including methane, propane, butane, liquified natural gas.
Gas (unconventional)	*Non-renewable*. Shale gas, methane hydrates, coal-bed methane, aquifer (water dissolved), coal gasification. Excluding gas from pyrolysis where the fuel is waste and methane is by-product. For AD, the fuel is also waste (animal and human), but it can be considered as renewable (see biogas).
Hydro	*Renewable*. Large devices at the MW scale not part of a two-level pumped storage scheme, nor tidal barrages.
Hydro (low head)	*Renewable*. Community-scale, kW devices for rivers.
Nuclear (fission)	*Non-renewable*. Including thorium.
Nuclear (fusion)	*Non-renewable*. Meaning deuterium and tritium.
Oil	*Non-renewable*. All grades of conventionally extracted oil.
Oil (unconventional)	*Non-renewable*. Shale oils, tight oil, extra-heavy oil, bitumen. Includes coal-to-liquid.
Ocean (tidal)	*Renewable*. Subsurface stream devices and lagoons.
Ocean (wave)	*Renewable*.

Peat	*Non-renewable*.
Solar (electric)	*Renewable*. Photovoltaic including IR wavelength devices.
Solar (thermal, power)	*Renewable*. Mostly MW-scale concentrated solar power devices for raising steam, excludes solar water heating for buildings.
Solar (thermal, water)	*Renewable*. Mainly for building-scale uses, distinct from concentrated solar power.
Solar (updraft tower)	*Renewable*.
Thermal (geological)	*Non-renewable*. Producing hot water for direct heat exchange or steam for electricity generation. Includes minewater systems.
Thermal (low temperature)	*Renewable*. Low grade thermal energy drawn from the near sub-surface environment.
Waste	*Non-renewable*. Municipal solid waste, plastics, tyres. Energy recovery by incineration or pyrolysis, plus AD. For pyrolysis and AD, the processing to produce methane and hydrogen is a by-product of waste management in this study. For AD see Biogas.
Wind (offshore)	*Renewable*.
Wind (onshore)	*Renewable*. Excluding micro turbines.

Table 1 indicates whether the fuel source is renewable or not, using the common classification. An alternative terminology, ‘carbon-free’, has been suggested by Harvey (2010), but this would be unhelpful in our analysis which is concerned with the whole supply chain. Nuclear (fission), like Solar (electric) and Wind (off- and on-shore), may be carbon-free, yet clearly fissionable fuel is exhaustible and non-renewable. Categorising a fuel as renewable or non-renewable is mostly self-explanatory, but two interesting cases emerge namely Thermal (geological) and Waste. Many authors categorise geothermal energy as renewable (Stefansson, 2000; Turkenburg *et al*., 2012; Skea, 2015) whilst Harvey (2010) classes it as carbon-free. Geological reservoirs of thermal energy are exhaustible (Nazroo, 1989; Younger, 2014), only replenished (if at all) on geological timescales and therefore we class it as non-renewable. Waste, on the other hand, could be considered as renewable since replenishment is at a considerably faster rate. However, as the total amount of waste available is solely a function of societal behaviour, we take Waste to be non-renewable.

The categorisation of the bio-derived fuel sources is difficult and for the sake of clarity we have broken our nomenclature rule. Biogas (except landfill gas and sewage gas) and Bioliquid are not strictly sources, but manufactured products derived from Biomass, which is therefore the fuel source. However, their manufacture cannot be wholly incorporated into Biomass (solids) as the process pathways threaded through the stages are entwined and technically coupled to different degrees at different points making a complicated story. As there are several distinct end-uses (and final energy vectors) the risks more readily relate to the conversion technology (Stages 3-4), the distribution method (Stage 5), and the use (Stage 6). In part, the complexity arises from the immaturity of some process pathways and the marginal economic benefits.

Heat pumps are treated differently, depending whether they are exchanging heat with atmosphere or ground. The ground temperature at 1-2m depth varies little seasonally and acts as bidirectional storage where thermal energy (the ‘fuel’) can be extracted and rejected thermal energy deposited. The principal technologies are ground-source heat pumps and ground-water heat pumps. The fuel for air-source heat pumps is the sun (by various mechanisms) heating the air. However, we treat these as electrical devices (demand) because the rejected heat during the summer is lost to the atmosphere – air cannot act to store thermal energy in the same way as the sub-surface. Schemes for recovering thermal energy from minewater share technical characteristics with Thermal (geological) and are classified as such.

Demand Reduction (DR) has been included as a hypothetical fuel, ‘negafuel’, a mechanism influencing demand. There is precedent for considering demand reduction in the same framework as supply-side mechanisms: Eyre (2013) proffered a scheme to incentivise energy efficiency using a feed-in tariff to operate in a similar manner to those for renewable power generation. Our procedure is to apply the same analysis to DR as other fuels, to identify its risks and potential contribution to energy security. We understand DR as comprising two main elements: improved energy efficiency through use of or redesign of devices, and change in behaviour by people. This excludes small-scale generation technologies (covered by other fuels) but does include technologies such as a metering and control (Hinnells, 2008). The energy efficiency of homes and businesses is in part about the interaction of technical innovations and the willingness of people to adopt them and adapt their behaviours. Direct provision of energy services such as heat networks with water as the energy vector (both industrial and residential) or the provision of lighting or cooling, may lead to a reduction in demand through efficiency gains of scale. However, the relevant causes of risk are included elsewhere, so to avoid double-counting we exclude these from the definition of DR. The provision of heat is especially difficult to categorise as hot water is an energy vector and the plant supplying it might be waste low-grade heat from industry or a dedicated unit fired by another fuel. This is treated in Stage 6 (Use) of the relevant fuel.

2.2 Process stages in energy supply chains

The descriptors for processes and activities have been made explicit where possible, but where the range is wide, generic labels have been used. The point is to give a link to the level of complexity or scale of the operation to assist in assessing the risk specific for that fuel at that stage. Furthermore, using the PAM, the identified impacts result from processes. Thus, to assess risk we must first identify the processes (activities) involved with each fuel.

Analysing the fuel supply chain and processing system using the PAM, we suggest that the following high-level stages are appropriate for the scale of this study (Fig. 2):

1. Exploration for energy resources: Measuring the potential of the fuel source. Activities include geological prospecting and seismology, wind surveys, assessments of water and plant resource together with ecology, collecting data relevant to specific sites (above or below ground / sea).
2. Exploitation of the raw energy resource: Production, capture, and transport of raw resource. Design and construction of facilities, operation, import/export of product. Transporting resource (or raw material) to the mine/site entrance, and/or to the processing site for upgrading.
3. Conditioning the raw energy resource into fuel: Condition, process, and transport the raw energy resource to upgrade into a fuel which meets specifications for sale.
4. Conversion of the fuel to the final energy vector: This includes storage in the form of electricity, pumped (potential), thermal, and kinetic energy.
5. Distribution of the energy vector for sale to the end user: This includes the design, construction, monitoring, and maintenance of distribution infrastructure.
6. Use of the final energy vector: The users are households, agriculture, commerce and industry, public sector and private sector institutions; uses include transport and other engines, electrical devices and machinery, heating/cooling systems, and process plant.

The fuel supply chains are modelled on the key processes in all extractive industries. All stages include consideration of disposal of waste, site decommissioning, technical innovation, and efficiency. Stages 2-6 include the risks of project development. An important reason for being explicit about use

(Stage 6) is that impacts and risks can be readily associated with that stage. This strikes a balance of too many to be manageable and too few to be meaningful.

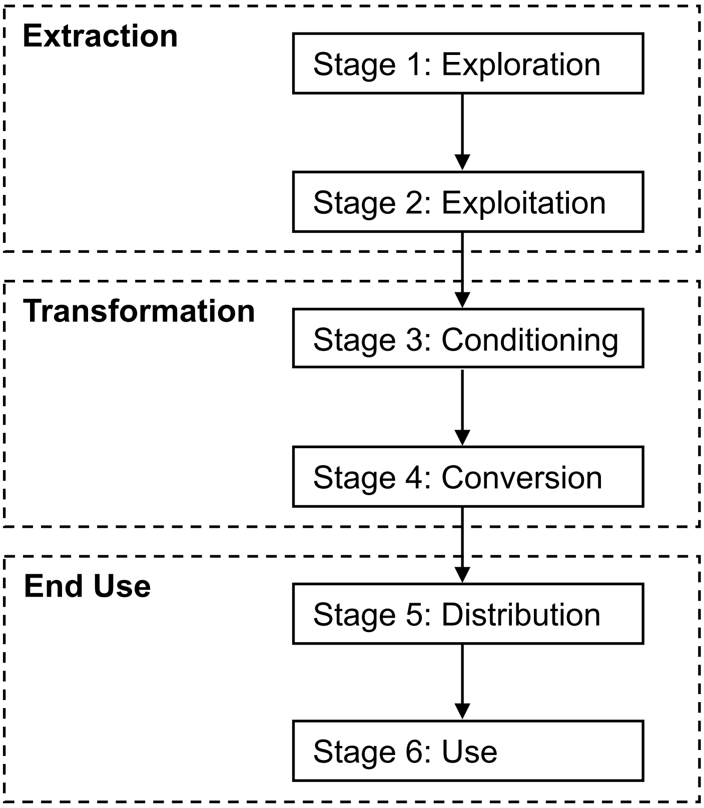


Fig. 2. The six process stages of the fuel supply chains. The three groupings of extraction (Stages 1-2, transformation (Stages 3-4), and end use (Stages 5-6) are broadly useful, though renewable fuels often have Stages 2-4 co-located at the conversion site.

Transportation of resources, materials, and fuels is required within stages (intra-stage) and between stages (inter-stage). Different forms of transport (bulk carriers, road, train, shipping) are involved each with different risk profiles, and we account for these transport risks where they arise at each stage. The reason for making transport more prominent is that it is often neglected in energy systems models, or only acknowledged through price. This underplays the importance of the risk associated with moving very large quantities of fuels.

Analysing the whole supply chain for each fuel in terms of the six stages shows that some stages are not relevant for some fuels because those processes or activities are co-located (Fig. 3). Some fuels do not require transportation, for example when exploitation, conditioning and conversion to final energy vector (Stages 2-4) are all located together at the source. For example, wind turbines and hydropower schemes convert fluid energy (wind, water) to electricity at source. Therefore stages 2-4 may be combined for Wind (offshore) and Wind (onshore). This is a pattern common to many renewables: Hydro, Ocean (tidal), Ocean (wave), and Solar (electric). For Solar (thermal, water) and Thermal (low temperature) there is no distribution stage as they generate low-grade thermal energy which can only be used locally. For some fuel categories the distinction is less clear-cut. An example is Thermal (geological), where the fuel source (heat) is extracted on-site, but the water required to inject into the rock formation may well have to be transported to the site. This is co-locating extraction and conditioning of the resource, but not the conversion.

Chemical processing has a wider definition, but the plant and site requirements will frequently be of similar complexity and size. Furthermore, the levels of safety requirements (and risks) will be generic. The Biogas, Gas, and Gas (unconventional) chains share a different characteristic in that the fuel leads to two forms of final energy vector – electricity and heat – depending on whether the gas is used by a power generator to make electricity or by end-users to make heat.

We take Demand Reduction to be applicable to activities of the end-user, including transport. In particular we consider that its Stages 2 and 3 are best captured as information (and education) and design activity. Stages 4-6 concern the deployment and use of devices to aid energy efficiency and the practice of modified behaviours.

2.3 Storage and Interconnectors

Many fuel supply chains require storage for inventory or to manage variability (e.g. for renewables). We assume that appropriate provision (e.g. storage tanks, batteries) is in place to handle the normal variation of supply and demand. The risk assessment of such facilities is included within the process stage where it occurs.

Grid-scale storage and interconnectors are considered at the distribution stage. Even though grid-scale storage would naturally be considered a security of supply matter (for balancing intermittent renewables) it is not a primary fuel, being mediated by an energy vector (the electron) which is already in the distribution system. Usually electrical energy is converted into another form such as chemical, kinetic, or gravitational potential which is readily stored and converted back to electricity when required. Grid-scale storage, functionally indistinguishable from a generator, is not included as a fuel in Table 1.

Interconnectors (crossing the system boundary) possess an interesting status. Interconnectors are infrastructure, but they could be considered as a fuel with a geographical offset, extracted and transformed in one country and used in another. Moreover, interconnectors exhibit some of the characteristics which we associate with storage, such as acting as an additional balancing mechanism for supply and demand. The definition becomes blurred with pure infrastructure when considering structures such as a 'North Sea Grid' linking off-shore wind with several countries including those operating two-level pumped storage systems.

Stage	**Fuel Category**								
	Bioliquids	**Demand Reduction**	**Gas**		**Nuclear (fission)**	**Thermal (geological)**		**Thermal (low temperature)**	**Wind (offshore)**
1. Exploration	Find energy and waste crops	Measure potential	Geology, drill		Geology, dig	Geology, drill		Measure potential	Measure potential
2. Exploitation	Gather energy and waste crops	Create devices, services and communication campaigns	Drill and operate well		Mine	Drill and operate well		Operate heat pump	Operate turbine
3. Conditioning	Chemical processing		Chemical processing		Chemical processing				
4. Conversion		Operate electrical devices, heat, vehicles, or social practice	Combustion (CCGT)		Reactor	ORC turbine			
5. Distribution	Tankers		Electricity networks	Pipeline (gas)	Electricity networks	Electricity networks	Pipeline (water)		Electricity networks
6. Use	Vehicles		Electrical devices	Heat (onsite)	Electrical devices	Electrical devices		Heat (onsite)	Electrical devices

Fig. 3. Principal activities at each stage for selected fuel categories, Illustrating the co-location and bifurcation of stages. ORC is Organic Rankine Cycle, and CCGT is Closed Cycle Gas Turbine

2.4 Categories of risk

All risks originate in either the natural environment or human activity. Informed by a literature review, we have broken the two sources into seven distinct groups which readily arise from energy security considerations, namely: Economic, Environmental, Innovation, Manufacturing, Political, Skills, and Technical. These capture the broad and niche concerns expressed by a wide range of researchers across the spectrum of disciplines.

In their work on risk metrics Johansen and Rausand (2014) describe 11 desirable criteria which a metric should meet: validity, reliability, transparency, unambiguity, contextuality, communicability, consistency, comparability, specificity, rationality, and acceptability. We use these as a guiding principle for selecting the causes of risk. There were a large number of generic risks which could have been included, but the list needed to be kept to a manageable number – a number just large enough to describe a complex system at a high level. From experience using the PAM to find indicators for complex systems (Darton, 2017), we consider that the number of generic risks should not exceed around forty. Initially, from the literature, more than 80 issues which could be interpreted as causes of risks were identified. Some of these were found to be suitable for the scale we are considering, and could be captured in the generic definitions. Others were unlikely to have impacts beyond a single project, so were not suitable for a high-level analysis. Some were unique to a single fuel or nation, which could be incorporated into another broad category, often political. Our analysis is based on 34, listed (Axon and Darton, 2021b) in **Table A.1**, **Table A.1** noting that:

1. The category is the cause or source of the risk, then the specific risk is interpreted in the context i.e. activity of each stage. The practice of interpreting the risks is manifest in the form of a question.
2. The risk being considered is the risk to the energy security of the nation or bloc (within the system boundary), not the risk to a project or company.
3. In any single fuel supply chain (at any or all stages) there may be multiple supply-countries with different characteristics e.g. standard of governance.
4. Some risks will have two parts even within a single stage – one for inside the system boundary, one external. We select the more significant element for our assessment.

3 Method for constructing the risk matrix

The risk matrix records the risk score (likelihood multiplied by impact). Each element of the risk matrix includes supporting information: a visual indicator of the consequence level (defined in Table 4), the location of the cause of risk (inside or outside of the system boundary) and a note to remind the reader of the main technology or activity for which the risk assessment is being made. The final list of causes of risk remains generic, but the numerical levels of impact and likelihood are specific to the geographical area under consideration as defined by the system boundary, and are not specific to projects or a company.

3.1 Selecting the causes of risk for each stage

As the risks identified are generic, each stage is considered separately to establish whether the cause of the risk is relevant to that particular stage – it is only the actions in the stage that contribute to the potential risk. In the matrix, the same cause of risk may occur at more than one stage. Double-counting is avoided because risks are risks whenever they occur. There are a small number of causes of risk such as *poor institutional governance* and *lack of social stability* which are recorded once only, at their first occurrence in the fuel supply chain for a particular location. However, the risk is re-evaluated and recorded a second time if the chain crosses the system boundary i.e. consecutive stages change from being global in nature to being country-specific. The procedure for selecting which causes of risks need to be considered for each stage is:

1. These are risks at the location of the activity associated with that stage for that fuel source irrespective of where the fuel supply chain crosses the system boundary. Many fuel sources

will not only be scattered globally, but may also be present inside the system boundary. In many cases, however, the availability of that fuel source inside the boundary will be low. Where the availability of sources of that fuel is relatively evenly balanced (inside and outside the system boundary) e.g. oil and gas, conduct the assessment for the one that is increasing in volume. A detailed disaggregated study may separate these sources and conduct analysis on them independently, if required.

2. Risks included are those which have an impact on whether the activities in the stage can proceed or not. If the cause of risk is unlikely to stop or hamper the activity, it is unlikely to be a relevant cause of risk for that stage.
3. 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.

The level of the risk associated with a particular cause of risk can vary between fuels at a particular stage. For example, in the first stage – exploration – the cause of risk *lack of access to capital* is important for oil and gas where exploration is costly (on- or off-shore), but for biogas minimal investment is required for exploration; for exploitation and conversion, access to capital is likely to be important for most fuel sources. A second example is that a *changing policy or regulatory framework* might not deter exploration of a particular fuel source in the first place, but might well deter subsequent exploitation. Risks which are not significant for at least one fuel at a particular stage are eliminated from consideration for that stage. 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 for many fuel sources any exploration scheme is small by definition any spillage or escape of resource into the environment will have a limited impact.

The first stage (exploration) is different in nature from the other stages since this stage produces information and not an energy vector (there is no commercial production at Stage 1). Nevertheless, exploration does have an impact on energy security: the principal risks are *Unable to agree a price for licence or permits* and those associated with fuel quality.

The fuel categories need to be thought about a little differently at the distribution and use stages, since the risk sources here are based on the final energy vector that is produced at conversion rather than the raw fuel source. For example, diverse fuel sources are converted by different technologies into electricity which is distributed to consumers, but with liquid fuels for transport, different impacts occur at the use stage where the public operates the ‘conversion’ devices.

3.2 The risk score and consequence level

First we define the likelihood and impact, and the consequence level implied by the risk score, drawing on best practice guidelines for risk rating matrices given by Standards Australia (1999), IRM (2013), Duijm (2015), and Baybutt (2018).

Likelihood is commonly assigned using a five-point scale. However, this is more appropriate for a clearly defined project or organisation where the risks are also more clearly defined, and where more precise quantification is meaningful and often essential. For a high-level analysis of a system with a degree of risk aggregation as proposed in this work, it is not meaningful to quantify risks in such detail. Furthermore, the longer-term nature of the risks involves considerable uncertainty. The interesting and useful interpretation of long-term risks is in understanding their relative importance, so broad bands representing likelihood are sufficient. For different types of risk, probability or frequency may be more applicable. We have adopted a three-point frequency scale (Table 2).

Table 2
Approximate time-scales describing the frequency of risk events.

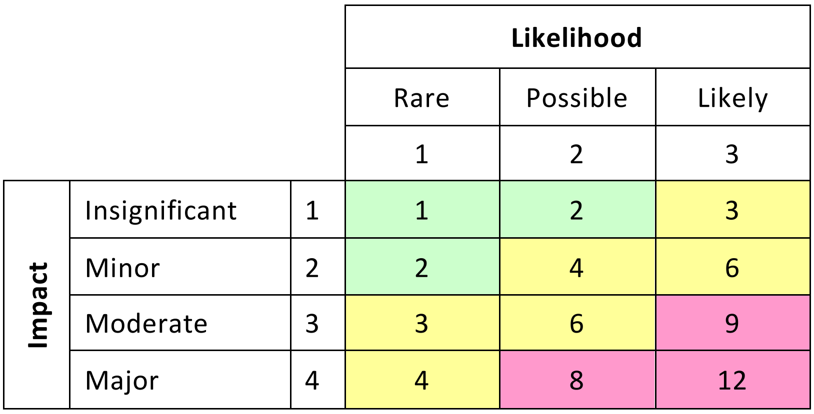
Descriptor	Level	Frequency	Definition
Rare	1	<< once per 10 y	Only occur in exceptional circumstances
Possible	2	Once per 10 y	May occur
Likely	3	Once per 1 y	Expected to occur

Descriptions of the impacts and their levels need to be scale-independent i.e. not be related only to project- or company-level activity, however, they must encompass such. Many risk analyses use three or five levels to describe the impacts of identified risks. However, we have chosen a four-point scale (Table 3) to force the analyst to positively select a response above or below the middle value. Furthermore, for high-level analyses across the full range of fuel supply chains, subtle distinctions for broad categories are not always meaningful. For project-level analysis greater disaggregation is essential for operation efficacy. We tested a five-point scale with 'catastrophic' as the most extreme impact (enforced cessation of activity), but found such a definition not to be particularly helpful. The four broader descriptors make it easier to capture the essence of the risk for a fuel at different stages in the supply chain. Our generic definitions of the impact levels (Table 3) are consistent with the idea that the degree of risk depends on the system's capacity to cope with the consequences of a risk event, and recover from it (Vlek, 2013).

Table 3
Summary of the definitions of the impact levels.

Descriptor	Level	Generic Definition
Insignificant	1	Any impact is only at the edge of 'normal' or accepted operation.
Minor	2	Recoverable short-term loss of activity, delay, or function.
Moderate	3	Recoverable, but sustained delay, loss, or change in function.
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.

As the product of the impact and likelihood scores (Fig. 4) determines the consequence level (Table 4) there cannot be overlap between these categories. Since we are using a four-point scale and not five, it is defensible to leave rare-major events out of the high-level category. Thus, as there is a gap between six and eight, this is used to delineate the high and moderate consequence levels. Likewise, an insignificant impact that has a likely occurrence could be at the low or moderate level. We judge that a likely impact is not one that should automatically be considered as having a low-level consequence. Our risk rating matrix has validity since it obeys both of Cox's lemmas governing the requirements for weak-consistency (Cox, 2008), and avoids the pitfalls noted in section 1.2.



			Likelihood		
			Rare	Possible	Likely
			1	2	3
Impact	Insignificant	1	1	2	3
	Minor	2	2	4	6
	Moderate	3	3	6	9
	Major	4	4	8	12

Fig. 4. Combinations of likelihood and impact giving the risk score and consequence level.

Table 4
A guide to the broad meanings of the consequence levels determined by the risk assessment.

Consequence Level	Required Response
Low (risk score 1-2)	None – these risks are within the expected range for companies, governments, and societal organisations
Moderate (risk score 3-6)	Ranges from 'watching brief' to some action required (technical or policy)
High (risk score >6)	Mitigation plans must be in place, or policy needs immediate attention to reduce the risk level

To aid prioritisation of policy actions, we have devised a method to reach a composite score to indicate the overall risk of each fuel supply chain. Several characteristics need to be taken into account:

- the fuels which branch – at different stages – into pathways which produce different energy vectors, namely: Biogas, Biomass, Exotic gases and liquids, Gas, Gas (unconventional), Oil (unconventional), and Thermal (geological),
- the fuels share only five different distribution systems (electricity networks, road tankers, and pipelines for gas, oil, and water), and
- four different end-use types, namely: Electrical devices, Heat (onsite), Heat (network), and Vehicles.

It is not reasonable to attribute the full risk score to every fuel that shares infrastructure as 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, so can be simply summed to give a sub-total for the fuel's extraction and transformation. At stage 4 the branching points score zero. We assume that the risk for use (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, fuels which share onshore electricity networks with other fuels. The composite Total Risk Score (TRS) for a fuel f can be expressed as,

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

where:
S_i = sum of the risk score for the *ith* stage,
U_j = risk score of the underlying distribution *jth* infrastructure type,
m_j = number of fuels sharing the *jth* infrastructure type,
n_k = number of fuels sharing the *kth* use type.

The first term is the sum of Stages 1-4, the second term is the share of distribution risk corrected for any elements unique to that fuel, and the third term is the share of risk for the use stage. We consider this approach to be reasonable since it supports the marginal risk element of shared infrastructure. It also explains why introducing a fuel (or new use of an existing fuel) is so difficult when it requires a new dedicated distribution mechanism.

4 UK Case Study: calculating risk in fuel supply chains

The UK is a G7 nation, with a balanced renewable and non-renewable energy system, that has been leading in the setting of carbon reduction targets. The UK Government's view relating to energy security is set out in the Clean Growth Strategy (BEIS, 2017), though without explicit reference to the previous energy security strategy (DECC, 2012). The clean growth strategy focusses on short-term security of supply regardless of the fuel mix emphasising flexibility, adequacy, and resilience, whilst the 2012 strategy included longer term actions such as demand reduction. The consistent policy direction is the reliance on regulated competitive energy markets (Ofgem, 2017) to deliver diversity of supply and robust infrastructure. Changes in the capacity market mechanism for electricity supply are charted by Grubb and Newbery (2018) in their review of electricity market reforms (EMR). Also part of the EMR is the support for deploying new renewable generation through the 'Contracts for Difference' mechanism (BEIS, 2019). Playing a role at the local level, the community energy strategy (DECC, 2014, 2015) set out to support energy security and climate policy objectives by reducing energy bills, developing skills, and reducing costs. There is a tension within Government over developing energy policy, with Craig (2020) suggesting that "*… the Treasury doubts the necessity of rapid domestic decarbonisation, and instead orientates its policies towards a future in which such a transition occurs at a slower pace, if at all.*"; an example being the easing of the burdens on the UK oil and gas extractive industries (HM Treasury, 2014). The difficulties of translating energy policy into law is highlighted by Cairney *et al*. (2019).

In defining the system boundary for our study we use the extent of UK territorial waters (Great Britain and Northern Ireland). The UK is taken to mean England, Scotland, Wales, and Northern Ireland. However, we note that Northern Ireland's electricity grid is integrated with that of Eire. Northern Ireland accounts for approximately 2% of the UK population.

Of the 27 generic fuel categories listed in Table 1, eight were excluded from the UK case study for the following reasons.

- Unconventional Oil and Exotic Gases and Liquids: both marginal to UK supply.
- Nuclear (fusion) and Ocean (unconventional): both at experimental stage, yet to inject power into the network.
- Peat: cutting this non-renewable biomass is a small-scale rural activity, mostly in Scotland, carried out by householders. Usage is not recorded (BEIS, 2020), though the International Peatland Society estimates 20 kt per annum (WEC, 2013) mostly for horticulture.
- Hydro (low head): only makes a small localised contribution.
- Solar (thermal, power) and Solar (updraft tower): have no practical possibility of deployment in the UK. In the long-term, schemes for commercial Solar (thermal, power) might be sited in

Southern Europe or North Africa, but their contribution to UK energy supply could only be through a European Supergrid transmission system and then via interconnectors.

Therefore, 19 fuel categories are considered in detail in the UK case study.

The evidence base supporting the expert assessment of the likelihood and impact values is from meta-analysis using published data, interpretation and comment (with risk seldom directly articulated). A detailed description of the assessments is given by (Axon, 2019) and the results are summarised in Table 5. For 19 fuel sources, 34 causes of risks at six stages (plus birfurcated chains), there are 4420 individual elements to assess. However, after accounting for merged stages and some causes of risk that are not relevant for certain stages and fuel categories, the number of elements reduces to 2486 (56%). Further simplification is gained from the commonality for fuel categories sharing distribution infrastructure or end use mechanisms; although this does not reduce the number of elements that need to be assessed, the issues become repetitive and thus quickly decided.

Table 5
UK case study: overall risk ranking for the fuels (most risky at the top of the table).

Fuel	**Total Risk Score**	**Normalised Total Risk Score†**	**Rank**
Gas (unconventional)	436	100	1
Gas	430	99	2
Oil	427	98	3
Nuclear (fission)	409	94	4
Thermal (geological)	351	80	5
Biomass (solids)	285	65	6
Coal	283	65	7
Biogas	264	61	8
Bioliquids	209	48	9
Ocean (wave)	205	47	10
Demand Reduction	195	45	11
Waste	189	43	12
Ocean (tidal)	183	42	13
Thermal (low temperature)	162	37	14
Wind (offshore)	149	34	15
Wind (onshore)	139	32	16
Hydro	136	31	17
Solar (electric)	111	25	18
Solar (thermal, water)	88	20	19

† The normalised score is referenced to the maximum Total Risk Score.

Non-renewables tend to appear towards the top of the table (conferring more risk on the energy system) and renewables towards the bottom. In the centre are seven fuels which are a mix of renewable and non-renewables. The mean raw total for renewables is 175 and for non-renewables 340, approaching a factor of two greater. It is noticeable that the top four are all non-renewables and score much more highly than the main group (rank 6 onwards). There is a factor of five between the risk scores of the most and least risky fuels.

The bio-derived fuels are higher ranking than might be expected perhaps. For Biogas and Biomass (solids) stages 4-6 all carry significant risk, and for Bioliquids it is stage 3. Thermal (geological) is also a fuel source which would be perceived as low risk, however, all stages in fact present significant risks; the scale of the operations and the high likelihood of (technical) failure account for these levels of risk.

It is perhaps surprising that Demand Reduction is not at the bottom of the ranking since it is often described as 'the first fuel' (Rosenow *et al.*, 2017) suggesting that it should have the lowest risk profile. But it does not, which ties with the evidence that DR appears to be difficult in practice and under-delivers (Gupta and Gregg, 2020; Rau *et al.*, 2020) the supposed levels of saving, even accounting for the rebound effect. The lens of risk brings into focus the elements which are integral to the relative lack of success of Demand Reduction programmes. In comparing this negafuel with other fuel sources it is clear that meeting demand with supply from Solar (electric), Wind (offshore), and Wind (onshore) is a more straightforward task.

Fig. 5 shows which groups of the normalised total risk scores can be considered unique (a form of simple clustering) as listed in Table 6. In each of groups A, C, D and E the fuels have very similar scores. Thermal (geological) is difficult to attribute as it is located equidistantly between Group A and the other members of Group B to which it is assigned here. Solar (electric) and Solar (thermal, water) form the least risky pair (Group E). The fuel risk score is based on many separately quantified risks, so it is unlikely that fuels will change their group membership, unless there is a radical change in at least several categories of risk.

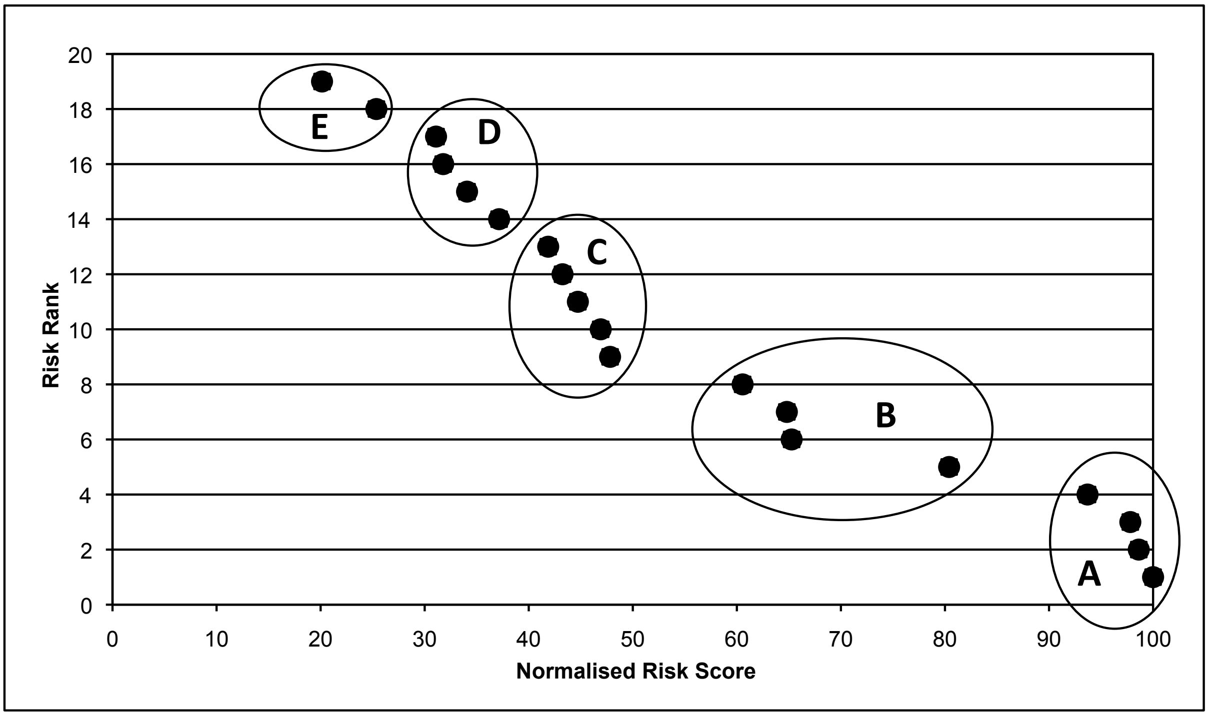


Fig. 5. UK case study: the total risk scores for the fuel categories cluster into broad groups.

Table 6.
Cluster memberships which are unlikely to change, though the ranking of individual fuels may vary over the medium-term.

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

4.1 Risk Variation by Stage

Identifying the stage at which a risk occurs and at what scale, can provide a useful prompt for more detailed analysis or guidance for potential policy action. Disaggregating the process into stages highlights the differences between renewables and non-renewables, in particular. At the level of individual fuels, we visualise how the risk score varies at each stage using radar plots (Fig. 6) with the shaded areas proportionate to the total risk score c.f. Nuclear (fission) and Thermal (low temperature). The total risk score is dominated by whether stages are merged or not (Fig. 3). Merged stages reduce the overall scores in general, and renewables have more merged stages than non-renewables (e.g. Wind (offshore). The Gas (electricity) and Gas (heat) charts shows how our method distinguishes fuels with branching points. Gas used for electricity generation yields a risk pattern different from gas used for heating, with the heat route giving a lower risk profile.

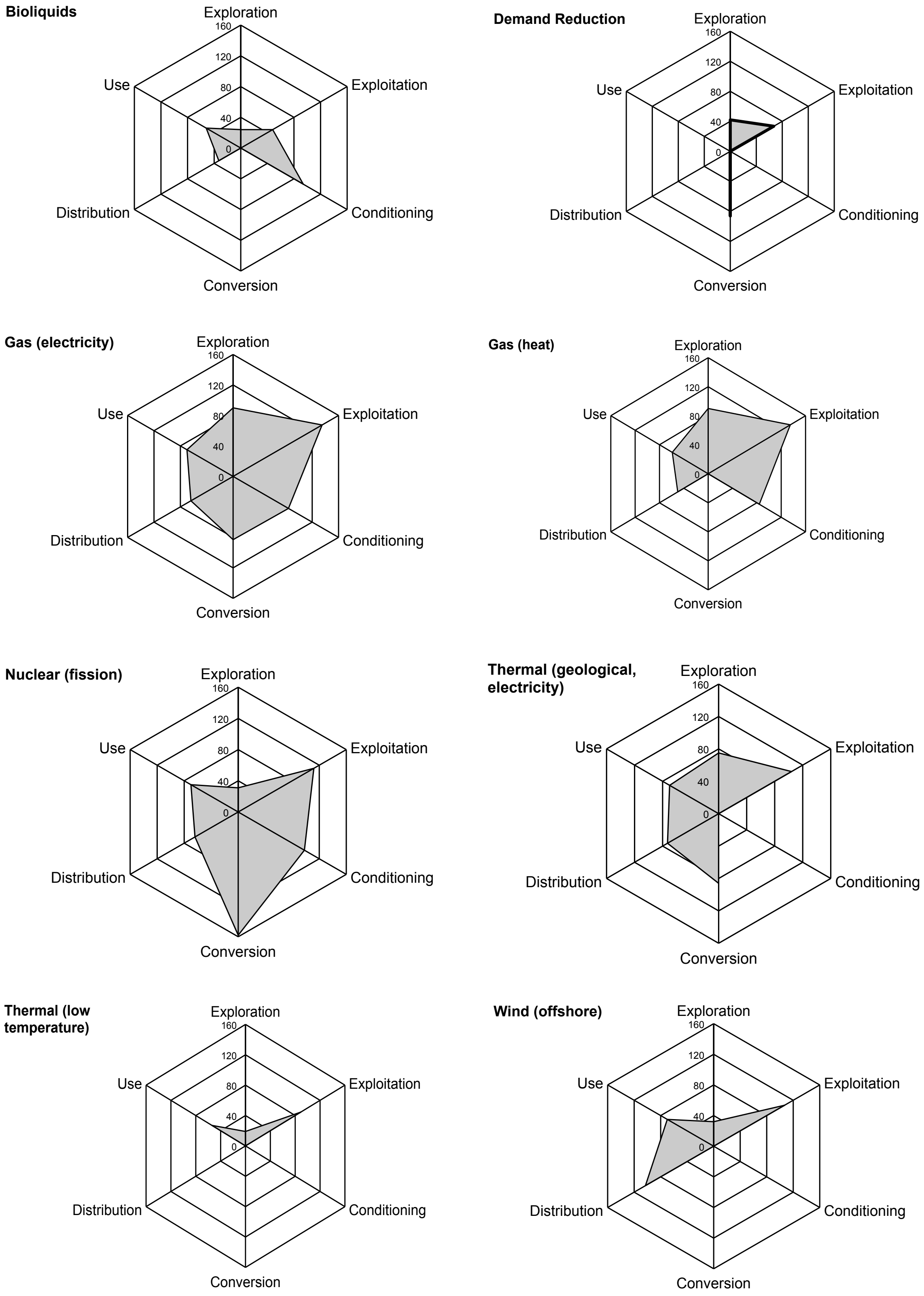


Fig. 6. Eight examples (three renewable, five non-renewable) of how the stage total risk score varies. Note that for Demand Reduction the exploitation and conditioning stages are unified, as are the conversion, distribution, and use stages, so the radial plot displays a spike value for the conversion stage. The absolute numbers for the stages risk scores are used for convenience.

4.2 Summary of Risk Characteristics by Fuel Type

We categorised fuels in Table 1 as either renewable or non-renewable; in Table 7 we give an overview of some important characteristics of the risk matrix for these categories.

Table 7
Significant characteristics for the renewable or non-renewable fuel categories.

Characteristic	Non-renewable	Renewable
Average total normalised risk score (a.u.)	78	40
Most significant cause of risk	Lack of access to capital	Changing policy or regulatory framework
Most significant risk category (sum)	Political	Innovation
Most significant stage (sum)	Stage 2: Exploit	Stage 2: Exploit
Fuel carrying the greatest risk	Gas (unconventional)	Thermal (geological)
Fuel carrying the lowest risk	Waste	Solar (thermal, water)

The results of Table 7 show that the renewable fuel category bears significantly lower risk than the non-renewable category, when considering the entire fuel supply chain. This conclusion differs from some previous analyses. For example, Tietjen *et al*. (2016) studied energy costs and prices and concluded that for renewable fuels, their “high capital intensity, weather dependence and uncertain production volumes” would introduce significant extra risks to electrical power markets, particularly as their market share increased. In contrast, the present UK case study identified “Changing policy or regulatory framework” as the most significant cause of risk for renewables, and “Innovation” as the single most significant risk category. Egli (2020) examined variation in investment risk for renewable energy in Germany, Italy and the UK, and found it to decline in general between 2009 and 2017; in the UK policy risk was consistently ranked high, perhaps as a result of frequent policy changes and policy inconsistency.

5 Conclusions

Using principles drawn from sustainability measurement and risk analysis research we identified a set of risks appropriate to the wide range of current and fledgling fuel sources. We demonstrate that creating a risk matrix to assess fuel supply chains as part of a national energy security assessment is a tractable proposition and that the set of causes of risk is able to accommodate fuels and processes with a wide range of production and operating scales.

Decomposing the energy supply system into staged chains allows the user to identify specifically where different risks occur and their spread, or concentration, in each chain. The fuel supply chains were each considered as six sequential stages to give structure to the analysis, but other deconstructions are possible. Using more stages would enable more features to be described and incorporated, but would increase the analysis effort and complexity of results. It is not helpful to add more detail to the analysis when this is later lost in re-aggregation, so a balance is needed, matching the degree of granularity in the analysis with the requirements for interpretation and presentation. Our analysis allows variation in the structure of the fuel supply chains. For example, Wind and Solar (electric) do not have a conditioning stage (stage 4), and both make use of a common electricity distribution system also used by other fuels.

We identified 34 unique causes of risk, grouped into seven categories. By critically assessing the broad energy systems literature we estimated the levels of likelihood and impact for each cause of risk for each fuel and each process stage – creating the risk matrix for the energy system. Impacts were evaluated using the triple-bottom-line methodology common in sustainability analysis, which takes separate account of effects on economic, environmental and societal capital. The impact level of a risk event was assigned according to the ability of the system to cope with the consequences and recover.

We conceived the sharing of infrastructure as lowering risk, as it reduces the number of different sorts of infrastructure needed, sharing risks between different fuel chains. The capacity of the shared infrastructure must be greater, and sharing introduces a systemic risk since failure will cause wider disruption, and this must also be considered when evaluating risk impacts. But in general, this sharing lowers the entry barrier for a new fuel source (lower risk) if it generates an energy vector already in common use. This helps explain why it is hard for district heating, say, to gain a foothold because such schemes require new infrastructure.

We identified 27 generic fuel categories, of which 19 were relevant for the UK. The fuel ranking (Table 5) shows that non-renewables (fossil fuels and nuclear) confer the greatest levels of risk on an energy system. The only non-renewable in the bottom (less risky) half of the table is Demand Reduction, and even that performed less well than might be expected – the risks involved have been under-estimated previously and field measurements have rarely demonstrated the energy savings predicted. Declaring efficiency as the 'first fuel' is not having the desired impact. Our work shows that it is not the first fuel – there are other more attractive options at present in the UK. Although advocates of demand reduction do not assume that it will occur without intervention or effort, many other actors in the energy sector appear to assume that it will. We recommend incorporating Demand Reduction in studies of energy security as a 'negafuel' or otherwise, to represent the essential demand side of the supply/demand balance. The relatively high risk-ranking of the biofuels is surprising at first sight. However, the chemical processing they require is often similar to that of conventional sources, involving risks typical of capital-intensive technology. Our risk assessment sheds light on why biofuels are not making inroads into the marketplace in the way that proponents have been hoping. The same is true for geothermal energy sources.

Assessing the detail of the risks and their relative importance for different fuels gives signals for the shaping of strategies to develop future energy systems portfolios. Although envisaged as an assessment method for national long-term energy security, our framework and methodology could be adapted for examining single fuel supply chains from specific sites (or nations), including international relations and other detailed knowledge, say. Our method makes transparent the location of risks, and the nature and magnitude of risk impacts, and can provide a useful prompt for more detailed analysis or guidance for policy action. Furthermore, our method for decomposing a supply chain into process stages could be applied to understanding how risks arise for commodities and services of other industrial sectors.

To improve energy security, a possible and logical response of policy to the fuel rank would be to support maximal use of each fuel starting from the bottom of the list and moving upwards to fill the lowest 'risk state' of the energy system to meet demand. However, we have not used any sort of resource weighting, so our method is blind to the capacity of technologies to deliver the final energy vector, the abundance of each fuel, and the availability of sites to deploy the conversion technologies (stage 4). So, for example, in the case of Solar (thermal, water), the panels can only deliver warm water which must be used locally. In the transition to a low carbon economy, a great deal of adaptation will be needed, as supply chains for renewables are scaled up to displace fossil fuels and meet demands of various types.

In many countries the emphasis of policy support has been on reducing the costs of deploying a particular technology or process, but progress towards decarbonisation has been patchy. In part this is explained by many renewables having similar risk scores so that there are no clear winners. As a result, all players compete for policy support, and the same investment capital, skilled labour, and other inputs. Recent UK policy has emphasised the role of markets and competition in providing low-cost energy, which, if it is renewable, will displace higher-cost fossil fuel. However, considering the sustainability impacts of the energy system as we do in our analysis, leads to an appreciation of where risks actually occur and thus where additional measures will be needed to promote decarbonisation. Our analysis shows that cost reduction of technology and devices alone is insufficient to deliver an efficient and more environmentally benign energy system because other factors (risks) such as changing policy and regulation can form a greater barrier. The failure of even low-cost renewable solutions to expand into the existing fuel market is sometimes described as 'market failure', but may result from a broad range of pressures from outside the fuel marketplace. Our whole-system risk-based analysis identifies the key elements on which governments and companies should concentrate resources and expertise to promote the low-carbon transition.

The UK's Climate Change Act of 2008 established the UK's independent statutory Climate Change Committee (CCC) to advise and monitor progress. But the frequently changing policy and regulatory landscape in the UK suggests that the country has not yet achieved a stable platform for energy (security) policy development. As interim emissions targets are missed, not only in the UK, and the magnitude of the climate challenge becomes clearer, it seems that the institutional response is falling short. In the UK, either the CCC, or a newly constituted body, could usefully have additional powers to give comprehensive advice on long-term energy policy, including energy security considerations. More generally, given the need for rapid and substantial change of the energy economy, it seems that many governments need to pay more attention to long-term energy security.

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Appendix

Table A.1 List of the causes of risk.

Category	**Cause of Risk**
Economic	Lack of access to capital
	Lack of a well-functioning market
	Price volatility
	Uncertain decommissioning costs
	Unable to agree a price for licence or permits
Environmental	Natural hazards
	Quality of fuel source
	Lack of critical materials availability
	Difficult physical access
	Lack of water availability
Innovation	Optimism bias
	Only marginal improvements likely
	Research and development capacity or capability does not match the challenge
	Lack of public subsidy
	Weak technology transfer environment
	Lack of material substitutability
Manufacturing	Insufficient capacity to construct sites
	Insufficient capacity to manufacture system components or conversion devices
	Insufficient rate of infrastructure construction
Political	Changing policy or regulatory framework
	Significant public concern
	Insufficient rate of improvement in, or lack of enforcement of, standards and codes
	Denial of permission to access sites
	Disputed landrights or resource ownership
	Lack of social stability
	Poor institutional governance
Skills	Lack of basic education levels in the local workforce
	Lack of vocational training of the local workforce
	Lack of specialists in the local workforce
Technical	Pollution event
	Operational failure
	Unable to neutralise waste at decommissioning
	Specialist equipment unavailable
	Infrastructure failure