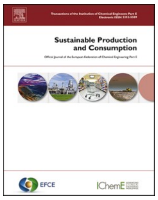
Sustainable Production and Consumption 47 (2024) 128–144

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



A systematic evaluation of risk in bioenergy supply chains

C.J. Axon [a,*], R.C. Darton [b]

[a] Institute of Energy Futures, Brunel University London, Uxbridge, London UB8 3PH, UK
[b] Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK

ARTICLE INFO

Editor: Prof. Rafiqul Gani

Keywords:
Biofuel
Biogas
Bioliquid
Biomass
Energy security

ABSTRACT

We introduce a novel method of evaluating risks of disruption to (bio)fuel supply chains. The biofuel landscape is complex, with multiple options for feedstocks and processing routes, but the type, size, and scale of risks are currently not sufficiently appreciated. As a consequence, the uptake of biofuels remains below expectation suggesting the need for comprehensive risk assessment. Our method of risk discovery and evaluation is based on a transparent and robust sustainability assessment framework, and exploits the richness of data and expert analysis available in publications. In a UK case study, we show that biomass (solids) has a similar risk score to coal, biogas being slightly less risky, with bioliquids being less risky still though more risky than wind and solar power. The most important cause of risk, 'changing policy or regulatory framework', reflects this fledgling industry's need for policy support. The second most important cause of risk is 'lack of access to capital', reflecting the scale of the process engineering required to convert biomass to tightly specified products which could substitute fossil fuels. Levels of optimism bias in the biofuel industry are high, leading to unrealistic expectations from complex technologies and dubious claims about the quantity of resource available. This, together with the wide variety and variability of feedstocks complicates the business case for biofuel investment. Bioenergy policy would benefit from a more nuanced understanding of risks which impede the widespread large-scale deployment of biofuels.

1. Introduction

Bioenergy was truly the first fuel, with evidence of the controlled use of fire by humans dating back at least 300,000 years (Dance, 2017). Burning wood for heating, lighting or cooking thus easily predates the use of wind- and water-power, those other renewable energy resources which have only been utilized in the last few millennia. To satisfy the increased demand for energy during the industrial revolution, wood was replaced by mined coal, and later by oil and then natural gas (Wrigley, 2010). However, concerns about climate change related to the emissions of greenhouse gases from fossil fuel combustion have provoked renewed interest in biofuels. For example, in the US a range of measures (US Department of Energy, 2024) dating back to 1970 has sought to stimulate the use of biofuels to replace oil (Gan et al., 2019).

It is possible to grow dedicated energy crops to produce fuels such as bioliquids for the transport market, or to replace natural gas. But there is a strong motivation for using agricultural or similar waste as it is a low-cost resource, and much effort has been expended in developing bioenergy technologies to convert waste biomass (Kassim et al., 2022). However, whether the feedstock is dedicated crops or waste, the supply chains are complex, localized, and many of the technologies required are large-scale process engineering endeavours. Fig. 1 generalises the most important biofuel production routes currently envisaged, indicating the wide range of mechanical and chemical processing involved. These routes can produce a variety of energy vectors for use by consumers.

The long-term (sustainable) production and consumption of biofuels is frequently proposed for applications where fossil fuels are hard to replace, such as aviation, and transport more generally. This has given biofuels a central position in the debate about sustainability and energy futures. As the IEA states "*Biofuels play a particularly important role in decarbonising transport by providing a low-carbon solution for existing technologies, such as light-duty vehicles in the near term and heavy-duty trucks, ships and aircraft with few alternative solutions in the long term*" (IEA, 2023a). Reflecting the potential importance of bioenergy – biogas, bioliquids and biomass (solids) – in the energy transition, there is a large and fast-growing literature dealing with all aspects of its use in replacing fossil fuels (Duarah et al., 2022). Other reasons for using biofuels include the improvement of energy security and the stimulation of rural development (IEA, 2023a; RAE, 2017; Skogstad and Wilder, 2019). A possible

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* Corresponding author.
E-mail addresses: Colin.Axon@brunel.ac.uk (C.J. Axon), Richard.Darton@eng.ox.ac.uk (R.C. Darton).

https://doi.org/10.1016/j.spc.2024.03.028
Received 19 November 2023; Received in revised form 17 March 2024; Accepted 24 March 2024

Nomenclature

Abbreviations

AD	Anaerobic digestion
a.u.	Arbitrary units
BECCS	Bioenergy with carbon capture and storage
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CO_2	Carbon dioxide
FIT	Feed-in tariff
GHG	Greenhouse gas(es)
ILUC	Indirect land use change
LCOE	Levelized cost of electricity
LFG	Landfill gas
MWh	Mega Watt hour
N_2O	Nitrous oxide
NGO	Non-governmental organisation
NO_x	Nitrogen oxides
PAM	Process analysis method
R&D	Research and development
TRS	Total risk score
TWh	Tera Watt hour

Symbols

f	fuel
I	impact
L	likelihood
m_j	number of all fuels sharing the *jth* infrastructure type
n	number of use types associated with fuel f
n_k	number of all fuels sharing the *kth* use type
r	number of distribution infrastructure types utilized by fuel f
R	risk
$S_{6,k}$	risk score for *kth* use type at stage 6
S_i	sum of the risk score for fuel f at the *ith* stage
U_j	risk score of the *jth* underlying distribution infrastructure type

enhancement of the carbon-saving potential of the use of bioenergy is offered by combining it with subsequent carbon capture and storage (BECCS). This makes an overall process that is potentially net negative i.e. it removes carbon dioxide from the atmosphere to give 'negative emissions' (Ahlström et al., 2023; DESNZ, 2023a). Though little deployed commercially, BECCS has frequently featured in energy scenario pathways to a low-carbon future, despite concerns about its viability (Babin et al., 2021; Creutzig et al., 2021; IPCC, 2023).

But there are also concerns that growing crops for fuel could have negative impacts such as upward pressure on food prices, and cause land-use changes which *increase* GHG emissions. Taking more land into cultivation and using more water for crop-irrigation could lead to deforestation and destruction of natural ecosystems, and increased use of fertilisers and pesticides. Detailed analysis shows that production and consumption of biofuels can cause a wide range of undesirable sustainability impacts (Jeswani et al., 2020; Osman et al., 2024). The International Energy Agency notes that introducing biofuels requires international collaboration on standards, research and technological development, markets and taxation, and sustainability assessment to avoid unintended consequences (IEA, 2023a).

Evidently there are many problems and hurdles still to be overcome to enable the sustainable production and consumption of bioenergy, suggesting that the presence of risk may not have been sufficiently recognized or evaluated. Risk can deter investment in new feedstock sources and new technology, discourage innovation both in commercial and technical areas, and confuse or undermine development of appropriate policy. The UK Royal Academy of Engineering report (RAE, 2017) recommended introducing a national risk-based approach to biofuels, in which those feedstocks and biofuels are promoted which present a low risk of negative sustainability impacts, whilst high-risk alternatives are disincentivized. A lack of rigour and oversight in quantifying the sustainability of biomass sources "*due to the potential risks associated with the complex supply chains*" has recently been recognized (NAO, 2024). If biofuels are to play a useful role in cutting carbon emissions and reducing environmental degradation, it is important to understand what the main risks are, where they occur, their significance, and their causes. However, reviewing literature on biofuel supply chains, (Habibi et al., 2023) remark that existing studies mostly focus on specific feedstocks or particular sources of risk (which they term 'uncertainty'). They conclude that there is a need to consider the wide variety of feedstocks and

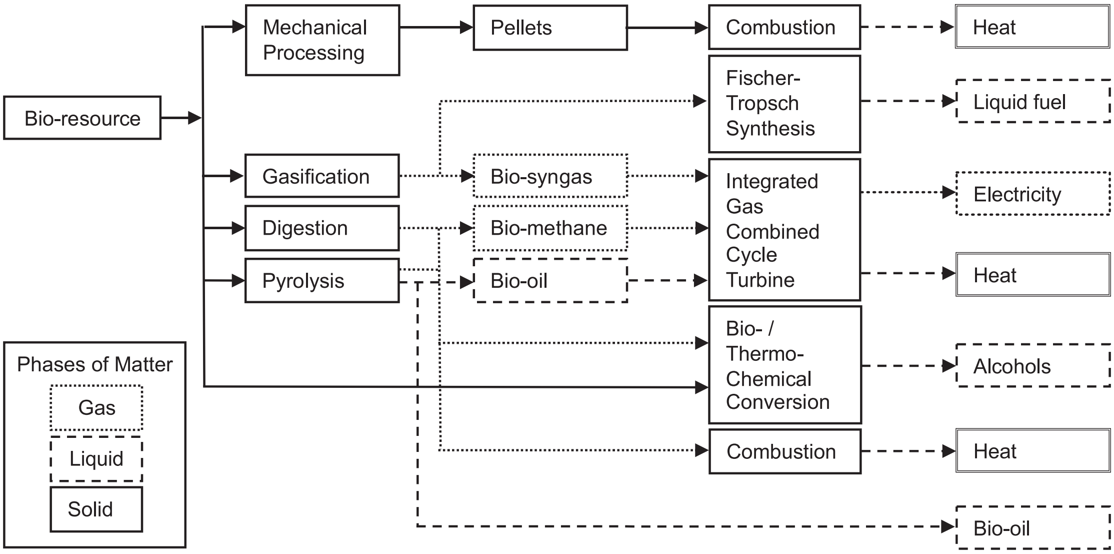


Fig. 1. The principal processing routes for biofuels, illustrating the complex nature of exploiting bio-derived materials and energy vectors.

processing routes available, and to identify all important sources of risk rather than those few commonly addressed. The lack of a comprehensive risk assessment of biofuels is the key research gap that we address.

Our aim is to describe and understand the entire risk profile for each of the three main biofuel types and to compare the risks with those of other current and future fuels. In Section 2, we briefly review policy drivers in major international bioenergy markets, and describe the main production routes which form the basis of our analysis, emphasizing the recognition of risk. We describe our method for risk discovery and assessment in Section 3. In Section 4 we present the literature-based justification for the more important risks for the UK case study, show how risk varies along the supply chain, compare risk profiles for biofuels with other fuels, and review our methodology. Finally we draw conclusions for policy and commercial operation, based on the risk analysis.

2. Review of the biofuels landscape

The wide range of potential sources of biofuel (Cavelius et al., 2023), taken together with the many possible processing routes that have been developed, present a complex picture. With complexity come risks, which may delay or prevent deployment, which must be recognized and managed when a new product is introduced to the market. Indeed, finding pathways to replace fossil fuels with biofuels has not proved straightforward, as shown by experience in the European Union (EU). Following measures to encourage the use of agricultural surpluses and waste material for energy, the EU finally enacted a Biofuel Directive (European Parliament, 2003), aiming to reduce CO_2 emissions particularly from transport, reduce dependence on imported fuels, improve air quality and encourage appropriate sustainable rural development. In 2006, a new strategy was proposed (European Commission, 2006), with new targets for biofuels following under the Renewable Energy Directive of 2009 (European Parliament, 2009). However, evidence was accumulating that producing biofuels could cause undesirable impacts, on food security and ecosystem health, and that anyway reductions in GHG emissions did not necessarily follow when fossil fuels were substituted by biofuels (Cadillo-Benalcazar et al., 2021). The Renewable Energy Directive was thus recast (European Parliament, 2018), requiring a more comprehensive sustainability assessment of renewable fuels. In particular for biofuels, this aimed to reduce the impact of Indirect Land-use Change (ILUC) which can cause significant GHG emissions, as well as loss of biodiversity and other ills. The 'European Green Deal' (European Commission, 2019) incorporated new targets for the market share to be taken by biofuels, with further restrictions to address the issue of ILUC. An amending EU Directive on Renewable Energy (European Commission, 2021) recognized the continuing risk that the biofuel market could negatively impact biodiversity and food supply. It appears from this history that early EU policy to promote bioenergy caused unintended consequences, perhaps arising from an over-reliance on economic indicators and mechanisms, and failure to consider whole-system behaviour. This has led to continuing policy adjustment. Many issues remain though, for example the need to harmonize policy between biofuel markets and those for other forestry and agricultural products, to prevent leakage and trade-offs between sectors (Mai-Moulin et al., 2021). However, without a comprehensive risk assessment of the whole bioenergy supply chain, it will not be possible to be sure that EU policy addresses all necessary steps of mitigation.

Notwithstanding these difficulties, the EU foresees a growing contribution of biofuels to its renewable energy portfolio, aiming to provide some 19 % of transport fuels by 2050 (Chiaramonti et al., 2021), the majority being advanced biofuels (which do not compete with food or forestry). The IEA collates data on both current and planned biofuel production, and reports that more than 80 countries have introduced policies to support biofuels, which in 2021 met about 3.6 % of transport energy demand globally (IEA, 2023a) and about 5 % in the US (EIA, 2023). Over the five-year period 2016 to 2021 the global consumption of biogasoline and biodiesel grew by 21 % (BP, 2022). However, the IEA (IEA, 2023b) warns of an approaching 'feedstock supply crunch' as biofuel demand threatens to exceed what can be produced from supplies of vegetable oil, waste and residue oils and fats in the coming period. For biofuels to play their expected role in a lower-carbon future (net-zero emissions by 2050), companies and governments will need significantly to improve supply chains, introduce new feedstock supplies and more efficient technology (IEA, 2023b). The IEA notes that markets are dynamic, and the high prices resulting from a tight supply/demand balance are a signal to seek out new supplies, and should prompt the development of government programmes and industrial innovation to ease the supply/demand balance. Estimates of future supplies of bioenergy must be treated with caution (RAE, 2017) because of the number of assumptions necessary concerning land use, competing markets, technology and farming innovation and changes in social habits. In particular, production of food and bioenergy are closely linked. Scenario-based estimates by (Errera et al., 2023) suggest that by 2050, biofuels could supply between 7.5 % and 36.9 % of global primary energy, saving emission of some 1.2–11.1 Gt $CO2_{eq}$ annually.

Increasing bioenergy supply effectively requires that risk be addressed. Pries et al. (2016) observe that significant global subsidies for biofuels have failed to stimulate establishment of a growing industry, and they attribute this failure partly to the poor appreciation of the risks facing companies active in biofuels. From a company survey, relating to USA and Canada, in addition to familiar management risks (e.g. obtaining qualified staff, managing innovation, etc.), they identified the important risks of biofuel policy uncertainty, volatility in expected prices of both feedstock and product, and uncertainty both in the availability of feedstock and demand for product.

Recognition of the consequences of competition for land between natural ecosystems, crops destined for human or livestock consumption (Goetz et al., 2017), and crops supplying biomass for fuel (Das and Gundimeda, 2022) has led to an evolution in feedstock strategy. First generation biofuels are produced from plant matter which has high oil content, or by fermentation of plant components like sugars and starches – but these are materials that could be used for food or animal fodder. Accordingly attention was switched to second generation (advanced) biofuels, generally derived from grassy or woody crops and agricultural waste not suitable for human or animal consumption (Periyasamy et al., 2023; Sun et al., 2023). Second generation biofuels require a good deal of processing, and thus expense, to turn the plant matter into an acceptable fuel, so third generation biofuels produced from biomass from algae were proposed (Abbasi et al., 2021; Sun et al., 2022). These aimed to reduce processing costs and use less land area and other resources, and avoid competition with food or fodder production, but costs remain a problem (RAE, 2017). Tuning the properties of specific algae by genetic engineering to improve their productivity leads to fourth generation biofuels. The necessary technology, and also the health and environmental risks are being actively researched (Abdullah et al., 2019). All these feedstocks can be processed in various ways to produce biogas, bioliquid or (solid) biomass as a product to be sold.

All biofuels used commercially are currently first or second generation. In the UK, our case study, biogasoline and biodiesel supply around 7 % of transport fuel demand. Some bioliquids are supplied to non-transport sectors, but this represents only 3 % of the UK bioliquid fuel total. In the UK, biofuels also make a significant contribution to electricity generation – in 2022 bioenergy and waste contributed 11 % of total electricity generation, compared to 25 % contributed by windpower (DESNZ, 2023b). The UK Government has formulated a strategy for exploiting biomass in its widest sense (DESNZ, 2023a).

2.1. *Biogas*

There is a wide variety of technologies and routes to produce biogas (Alves et al., 2023; Faizan and Song, 2023; Watkins and McKendry, 2015a) from feedstocks including farm wastes (Oreggioni et al., 2017), sewage sludge (Mills et al., 2014), food waste (Hunter et al., 2021), municipal solid waste (Watkins and McKendry, 2015b), algal biomass (Montingelli et al., 2015), and wastes and residues (El abdellaoui et al., 2023). The biogas can be upgraded to a liquid transport fuel (Ail and Dasappa, 2016). The other important source is landfill gas (LFG) (Brown and Maunder, 1994) which must be captured (or vented) for safety. Frank et al. (2017) suggest that bacterial stimulation may be possible to enhance LFG production.

Anaerobic digestion (AD) is well-established (Foster et al., 2021) and scalable because it can produce methane at grid specification (Fubara et al., 2018). Technology development has focused on farms (Gowreesunker and Tassou, 2016) showing that bigger units are more efficient (Oreggioni et al., 2017). There remains some uncertainty about the merits of biogas use onsite in a CHP unit versus grid injection. Mills et al. (2014) claim that grid injection is economically the best option but is poor for the environment, whilst Watkins and McKendry (2015b) state that onsite use is always the worst option (in part because of the very much higher efficiency of CCGTs).

2.2. *Bioliquids*

Various sources have been proposed as suitable for conversion and upgrading to 1st and 2nd generation bioliquids which could substitute for mineral oil products: corn (Acquaye et al., 2012), macro-algae (Gegg and Wells, 2017), *Miscanthus* (Shemfe et al., 2016), rapeseed (van Duren et al., 2015), straw (Glithero et al., 2013a), starch slurry (UKPIA, 2022), sugar beet (Cárdenas-Fernández et al., 2017), tallow (RAE, 2017), waste cooking oil (Acquaye et al., 2012), and willow (Glithero et al., 2013b). Future liquid biofuels (3rd and 4th generation) require exploiting waste and by-products (Saravanan et al., 2022), micro-algae (Thanigaivel et al., 2022), and genetically engineered organisms (Cavelius et al., 2023), with multi-purpose land-use to increase yields (Shortall et al., 2015). Sustainable aviation fuels have received much attention (Ng et al., 2021). Whitaker et al. (2018) give a useful overview of emissions arising from direct and indirect land-use change, and the link between land-use change and policy for biofuel (liquids) in the US has been investigated (Austin et al., 2022). For macro-algae production at scale, artificial cultivation will be required (Roberts and Upham, 2012) which may clash with other users of inshore waters.

Whilst there are some biochemical similarities between sources of biomass, the possible processing methods can be very different even for the same source. For dry macro-algae Milledge and Harvey (2016) show that direct combustion, pyrolysis, gasification, and trans-esterification to biodiesel are all possible processing routes, whilst for wet macro-algae hydrothermal treatment, fermentation, and AD are feasible. Syngas from gasified biomass – or other biogas – can be liquefied using the Fischer-Tropsch process (Ail and Dasappa, 2016). The hydrothermal liquefaction of biomass (Raikova et al., 2017) is a step towards biorefineries (Goswami et al., 2022). Using data from the historical development of the UK petrochemical sector Bennett and Pearson (2009) make a strong case for co-evolving fuel and chemicals production in biorefineries to produce high-value molecules such as pharmaceutical intermediates (Cárdenas-Fernández et al., 2017).

2.3. *Biomass (solids)*

Useful summaries of processes to exploit energy crops are given by Robbins et al. (2012), Foster et al. (2021), and Goswami et al. (2022). Sources of (solid) biomass proposed for the UK market to be used in combustion include waste wood (Röder and Thornley, 2018), *Miscanthus*, switchgrass, willow, poplar (Robbins et al., 2012). This heterogeneity explains in part why estimates of the available resource vary widely (Price et al., 2004; Slade et al., 2010; Mola-Yudego et al., 2017; Qi et al., 2018). Slade et al. (2011) give a clear overview of the problems plaguing estimation methodologies including the yield gap (the difference between estimated and actual biomass yields) confirmed by experiments (Mola-Yudego et al., 2015). Some estimates of the land available for UK biomass production are set as high as 40 % of the total area of Great Britain (Lovett et al., 2014), however, as Alexander et al. (2014) observe, many such studies do not fully consider environmental and social contraints, including the 'social licence to operate' (Baumber, 2018).

3. Method

We identify and quantify the significant risks arising in biofuel supply chains for the UK case study, using peer-reviewed and grey literature to provide supporting evidence. The grey literature includes reports by government agencies and non-governmental organisations (NGOs), commercial and journalism sources, both printed and web-based. Although risk is sometimes articulated explicitly in this literature, as with other fuels (Axon and Darton, 2021a) risk is more often only implied through mention of barriers, bottlenecks, challenges, concerns, difficulties, issues, problems, threats, uncertainties, and the like. Analysis is then needed to identify causative risks and appreciate their context and the resilience of the energy system to them. The methodology of assessing risk, which can be applied to all fuel sources in an economy, is fully described in (Axon and Darton, 2021a, 2021b), and a summary is given here. It is transparent, revealing all the factors contributing to the final risk assessment, so that these can be challenged, updated or adapted to differing circumstances.

3.1. *Defining the bioenergy supply chains*

Our approach is to derive the full range of causes of risk for the whole of each fuel supply chain. In the bioenergy family there are three separate chains, one each for biogas, bioliquids and biomass (solids), all of them considered renewable fuels. A supply chain consists of a linked series of stages starting with exploring for resources and ending with the use of a device exploiting the final energy vector by a consumer, as shown in Table 1. We find that using six stages to define each chain enables risks to be clearly identified in coherently grouped activities. In some cases stages are combined within a chain, and as shown in Table 1, bifurcation may also occur.

In the UK, biogas is methane produced from biogenic sources such as sewage, livestock manures, and agricultural waste for direct combustion or injection into the gas network. In some cases it shares similar production methods to bioliquids. Anaerobic digestion is a commonly used route exploiting farm animal waste. Off-gas from landfill sites is also considered in the biogas category. Bioliquid products include methanol, ethanol and biodiesel, and are produced from upgrading biogases or directly from biomass processing. They are mostly intended for use as transport fuels. Biomass (solids) is defined as crop and forestry residues, and aquatic biomass.

In this bioenergy family, complications – and risk – further along the supply chain arise not only from the number of different feedstock types, but their variability in specification and formulation. The search for suitable places to grow or gather resource constitutes the exploration stage and the gathering of resources is termed exploitation (stage 2), akin to exploration and production (E&P) for an oil or gas field. Each of the bio-resources requires different conditioning processes (Stage 3). The chemical processing and conversion required for bioliquids (Stages 3 and 4) is notably more technically difficult, being similar to what is required for oil. The biogas and biomass chains bifurcate at Stage 3; product from anaerobic digestion potentially can be injected into the gas grid (if it meets the composition specification), or used for for combustion (Stage 4, Conversion) for electricity generation (Stage 5, Distribution) or for direct heat supply to homes and businesses (Stage 5, Distribution). Likewise, processed biomass can be combusted for electricity generation, or supplied to homes for use in small-scale furnaces (Stage 6, Use) producing hot water; both these routes are minor players in the UK energy system. Bioliquids need to be distributed by tanker (mostly) for use (Stage 6) by consumers in vehicles (including trucks).

Table 1
Process stages and the activities characterizing them, for the three bioenergy fuels. Note the bifurcation in the biogas and biomass pathways.

Stage	Biogas		Bioliquids	Biomass (solids)	
1. Explore	Find agricultural waste		Find energy and waste crops	Find woody crops	
2. Exploit	Gather agricultural waste		Gather energy and waste crops	Gather woody crops	
3. Condition	Anaerobic digestion		Chemical processing	Mechanical processing	
4. Convert	Combustion (ICCGT)			Combustion (CHP)	
5. Distribute	Electricity networks	Pipelines	Tankers	Electricity networks	
6. Use	Electrical devices	Heat (onsite)	Vehicles	Electrical devices	Heat (onsite)
Final Energy Vector	Electron	Molecule (gas)	Molecule (combustable liquid)	Electron	Molecule (hot water)

The two input resource types (waste, or crop) split into five end-points with four different energy vectors.

For this UK study we make three simplifications. First, we treat (anaerobic) digestion as the principal route for biogas which produces methane at grid specification, unlike gasification which produces syngas. Second, methanol and bio-oil production are not considered further as their main UK market is in chemical production. Third, pyrolysis is omitted as it is a minor activity in terms of its contribution to fuel production.

3.2. Assessing risk

The risks under investigation are those which, through their impacts, might damage, delay or halt operation of the supply chain. The causes of risk, forming a risk register, are identified by screening the supply chains, in a similar manner to that of the Process Analysis Method (PAM) for discovering sustainability indicators (Chee Tahir and Darton, 2010; Darton, 2017). The PAM treats the domains of sustainability (economic, environmental, and human/social) as dynamic ‘stores of value’ i.e. they can be increased or decreased by system processes. This dynamic characteristic is useful when considering risk. We find that 34 causes of risk gives sufficient coverage of the important risks but also the necessary granularity to describe groups (or types) of activities for comparing all fuel types; the definition and interpretation of causes of risk avoids double-counting (Axon and Darton, 2021a). The 34 causes of risk can be grouped in seven categories (see Fig. 2), which proves convenient when communicating results of the analysis.

We use a risk matrix (Axon, 2019), a well-established self-consistent method of assessing risk (Baybutt, 2016, 2018; Duijm, 2015), whilst mitigating the potential pitfalls identified by Cox (2008) and Peace (2017). We use a 3 × 4 matrix for likelihood (L) and impact (I), evaluating the risk score (R) as the product of likelihood and impact so $R = L*I$. The impact is a measure of the expected supply chain disruption caused by that risk, should it occur. The descriptors for the levels of likelihood (with indicators of frequency), impact and consequence level/response have been carefully chosen using academic literature, industry and Government reports, and official statistics (where available e.g. accident rates from the UK Health and Safety Executive). The scores and descriptors are as follows:

Likelihood

- Rare: only occurs in exceptional circumstances (<<once per 10 years) – score 1.
- Possible: may occur (once per 10 years) – score 2.
- Likely: once per year – score 3.

Impact

- Insignificant: At the edge of normal or accepted operation – score 1.
- Minor: Recoverable short-term loss of activity or function – score 2.
- Moderate: Recoverable but sustained delay, loss or change in function – score 3.
- Major: 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, or, operation – score 4.

Consequence level and response

- Low (risk scores 1–3), no response expected.
- Medium (risk scores 4–6), watching brief or action required (technical or policy).
- High (risk scores 8–12), mitigation plans must be in place, or policy needs immediate attention to reduce the risk level.

Each of the 34 causes of risk is evaluated for every fuel at each stage (Fig. 2). This gives a possible total of 204 assessments to make for each fuel, but not all risks are relevant for all fuels or at all stages, reducing the number of assessments needed. Furthermore, many fuels share infrastructure at some stages e.g. electricity distribution, where the risk evaluation will be common, further reducing the number of assessments. However, a notable characteristic of the process stages of bioenergy is that the routes bifurcate so that one raw material can be the source for multiple energy vectors (in multiple states of matter) needing multiple chemical or manufacturing processes (Fig. 1). Calculation of the overall risk score for a supply chain is a sum of the risk scores at each stage for each fuel. However, the bifurcation needs to be accounted for, as does

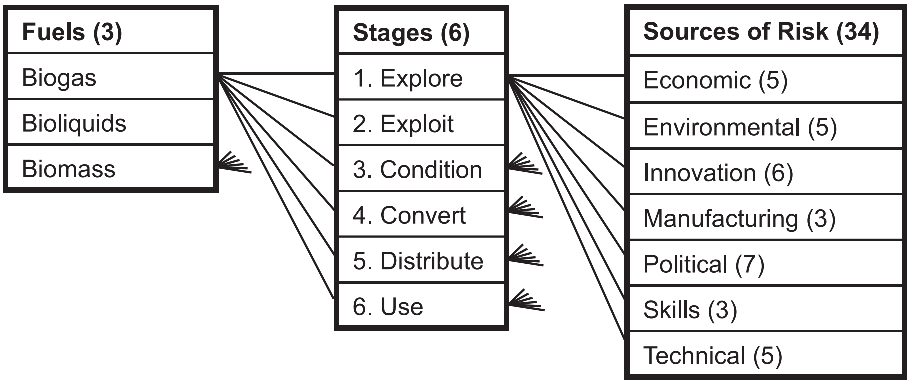


Fig. 2. The steps required to evaluate the total risk score for each biofuel.

shared infrastructure.

A fuel's total risk score (TRS_f) is calculated in the context of the complete portfolio of fuels in the UK analysis. The first term is the simple sum for the first four stages of that fuel supply chain. The second term accounts for the share of the risk associated with the distribution infrastructure. The third term is the share of the end use risk associated with the final energy vector, thus

$$\text{TRS}_f = \sum_{i=1}^{4} S_i + \sum_{j=1}^{r} \frac{U_j}{m_j} + \sum_{k=1}^{n} \frac{S_{6,k}}{n_k}$$

where: S_i = sum of the risk scores for fuel *f* at the *ith* stage, U_j = risk score of the *jth* underlying distribution infrastructure type, m_j = number of all fuels sharing the *jth* infrastructure type, r = number of distribution infrastructure types utilized by fuel *f* (Table 1), $S_{6,k}$ = risk score for *kth* use type at stage 6, n_k = number of all fuels sharing the *kth* use type, *n* = number of use types associated with fuel *f* (Table 1).

4. Results and discussion

Figs. 3–5 present the risk scores for the UK case study for the supply chains of biogas, bioliquid and biomass, respectively. Here we first discuss the literature-based justification for the identification of the high-level risks, and a selection of the more prominent moderate-level risks for stage 1–4 of the biofuels. Risks in the distribution and use stages of the final energy vector (Stages 5 and 6) and skills are then discussed as cross-cutting issues which are not exclusive to the bio-energy fuels group. Then we examine the distribution of risk throughout the supply chains of the biofuels, and compare overall performance with other fuels in the UK energy economy.

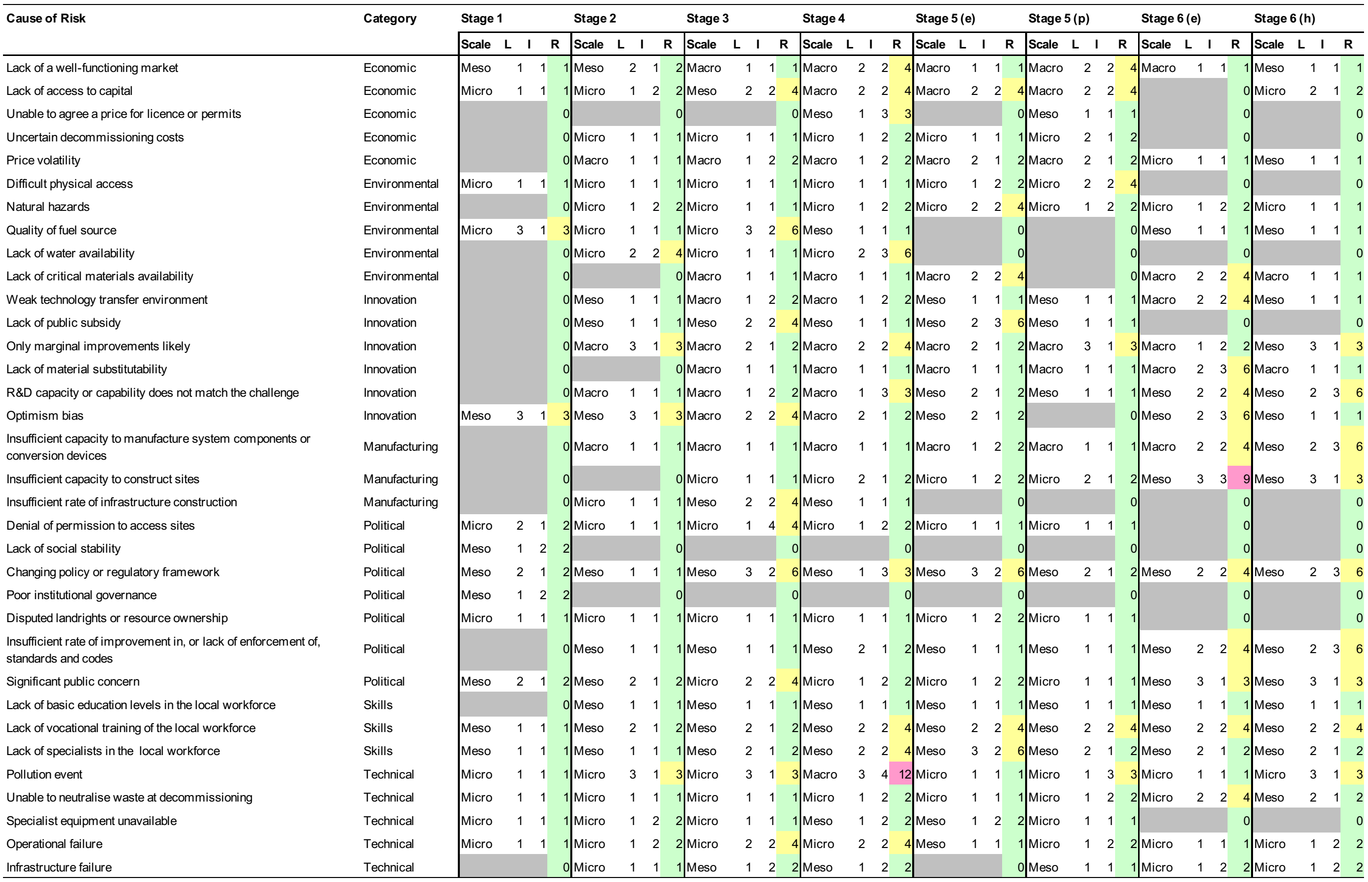
4.1. Biogas

Biogas has two high-level risks (one each at Stages 4 and 6(e)), but 59 moderate-level risks (Table 3) of which we consider 12 to be prominent. We do not see any significant causes of risk at stage one and two. However, stage two includes growing and/or gathering the fuel source, for which the risk manifests as the 'Quality of the fuel source' i.e. the variability (Röder, 2016; Zglobisz et al., 2010) e.g. some sources are seasonal. The variability in water content only becomes relevant to Stage 3. Court (2017) suggests that this variability is less of a problem for syngas production.

4.1.1. Stage 3

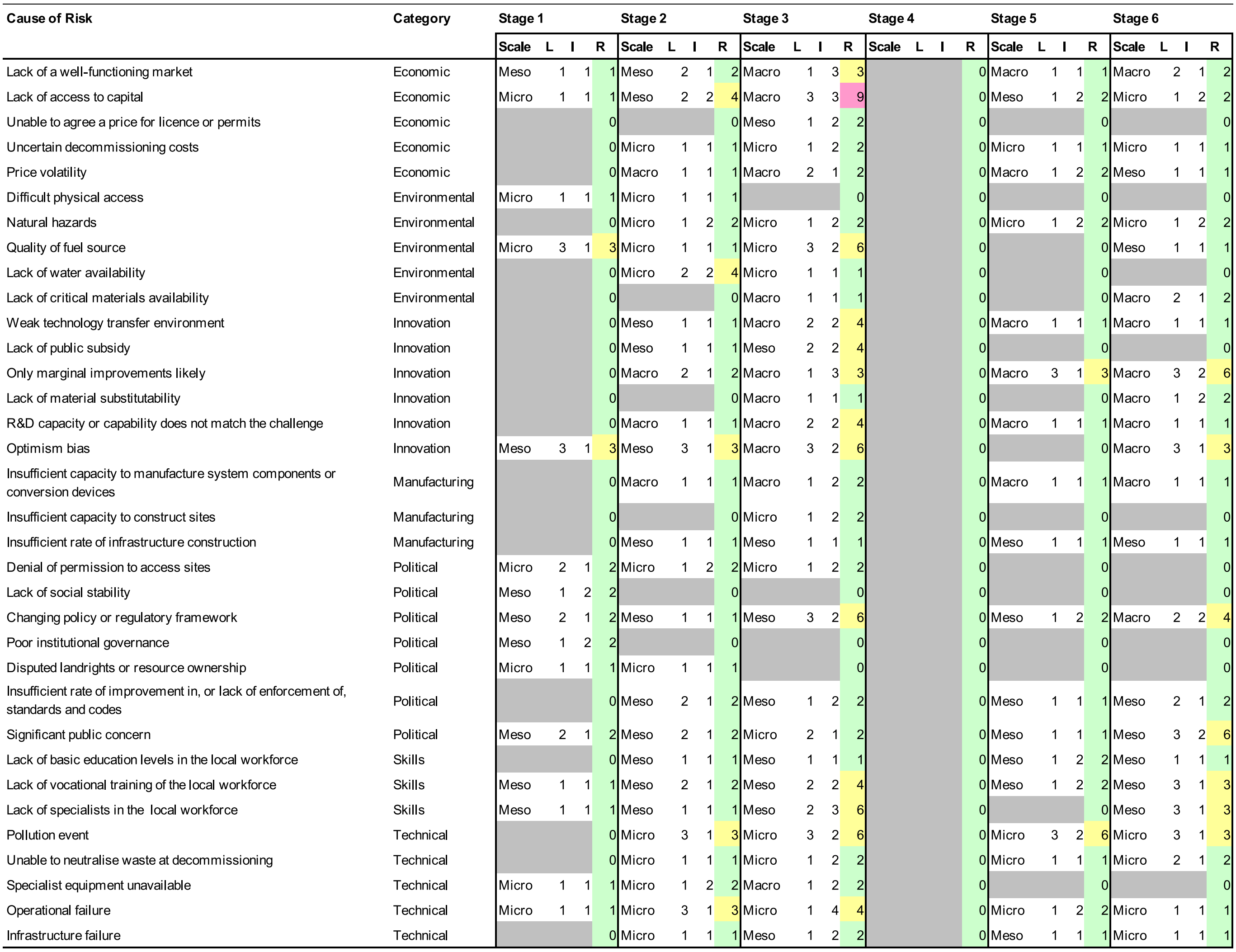
Access to capital is recognized as a risk for AD whether at the single farm scale or larger (Foster et al., 2021). Specifically, the rate of return (Tranter et al., 2011) and the cost of landfill (Zglobisz et al., 2010) are noted as the main influences. In the past, the 'Lack of access to capital' has been a problem for landfill gas (Brown and Maunder, 1994). Although the water content of the feedstock is an important signifier of the 'Quality of the fuel source', it is the carbon to nitrogen ratio which is the principal factor (Divya et al., 2015). We consider this to be a moderate risk.

Despite AD being relatively mature, there is evidence of R&D potential in, for example pretreatment processes (Carrere et al., 2016). LCICG (2012) note that R&D for AD will require continued public support. We suggest that the 'Lack of public subsidy' may occur, but might only lead to short-term disruption of activity. Connectivity of the gas grid (insufficient rate of infrastructure construction) is an issue for farms and other installations not located near urban areas, for example landfill sites.



Cause of Risk	Category	Stage 1				Stage 2				Stage 3				Stage 4				Stage 5 (e)				Stage 5 (p)				Stage 6 (e)				Stage 6 (h)			
		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	Scale	L	I	R
Lack of a well-functioning market	Economic	Meso	1	1	1	Meso	2	1	2	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1	Meso	1	1	1
Lack of access to capital	Economic	Micro	1	1	1	Micro	1	2	2	Meso	2	2	4	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4				0	Micro	2	1	2
Unable to agree a price for licence or permits	Economic				0				0				0	Meso	1	3	3				0	Meso	1	1	1				0				0
Uncertain decommissioning costs	Economic				0	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	2	1	2				0				0
Price volatility	Economic				0	Macro	1	1	1	Macro	1	2	2	Macro	1	2	2	Macro	2	1	2	Macro	2	1	2	Micro	1	1	1	Meso	1	1	1
Difficult physical access	Environmental	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	2	2	4				0				0
Natural hazards	Environmental				0	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	2	2	4	Micro	1	2	2	Micro	1	2	2	Micro	1	1	1
Quality of fuel source	Environmental	Micro	3	1	3	Micro	1	1	1	Micro	3	2	6	Meso	1	1	1				0				0	Meso	1	1	1	Meso	1	1	1
Lack of water availability	Environmental				0	Micro	2	2	4	Micro	1	1	1	Micro	2	3	6				0				0				0				0
Lack of critical materials availability	Environmental				0				0	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4				0	Macro	2	2	4	Macro	1	1	1
Weak technology transfer environment	Innovation				0	Meso	1	1	1	Macro	1	2	2	Macro	1	2	2	Meso	1	1	1	Meso	1	1	1	Macro	2	2	4	Meso	1	1	1
Lack of public subsidy	Innovation				0	Meso	1	1	1	Meso	2	2	4	Meso	1	1	1	Meso	2	3	6	Meso	1	1	1				0				0
Only marginal improvements likely	Innovation				0	Macro	3	1	3	Macro	2	1	2	Macro	2	2	4	Macro	2	1	2	Macro	3	1	3	Macro	1	2	2	Meso	3	1	3
Lack of material substitutability	Innovation				0				0	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	2	3	6	Macro	1	1	1
R&D capacity or capability does not match the challenge	Innovation				0	Macro	1	1	1	Macro	1	2	2	Macro	1	3	3	Meso	2	1	2	Meso	1	1	1	Meso	2	2	4	Meso	2	3	6
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Macro	2	2	4	Macro	2	1	2	Meso	2	1	2				0	Meso	2	3	6	Meso	1	1	1
Insufficient capacity to manufacture system components or conversion devices	Manufacturing				0	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	2	2	Macro	1	1	1	Macro	2	2	4	Meso	2	3	6
Insufficient capacity to construct sites	Manufacturing				0				0	Micro	1	1	1	Micro	2	1	2	Micro	1	2	2	Micro	2	1	2	Meso	3	3	9	Meso	3	1	3
Insufficient rate of infrastructure construction	Manufacturing				0	Micro	1	1	1	Meso	2	2	4	Meso	1	1	1				0				0				0				0
Denial of permission to access sites	Political	Micro	2	1	2	Micro	1	1	1	Micro	1	4	4	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1				0				0
Lack of social stability	Political	Meso	1	2	2				0				0				0				0				0				0				0
Changing policy or regulatory framework	Political	Meso	2	1	2	Meso	1	1	1	Meso	3	2	6	Meso	1	3	3	Meso	3	2	6	Meso	2	1	2	Meso	2	2	4	Meso	2	3	6
Poor institutional governance	Political	Meso	1	2	2				0				0				0				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2	Meso	1	1	1	Meso	1	1	1	Meso	2	2	4	Meso	2	3	6
Significant public concern	Political	Meso	2	1	2	Meso	2	1	2	Micro	2	2	4	Micro	1	2	2	Micro	1	2	2	Micro	1	1	1	Meso	3	1	3	Meso	3	1	3
Lack of basic education levels in the local workforce	Skills				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	2	1	2	Meso	2	1	2	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2	Meso	2	2	4	Meso	3	2	6	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2
Pollution event	Technical	Micro	1	1	1	Micro	3	1	3	Micro	3	1	3	Macro	3	4	12	Micro	1	1	1	Micro	1	3	3	Micro	1	1	1	Micro	3	1	3
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	2	2	4	Meso	2	1	2
Specialist equipment unavailable	Technical	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Meso	1	2	2	Meso	1	2	2	Micro	1	1	1				0				0
Operational failure	Technical	Micro	1	1	1	Micro	1	2	2	Micro	2	2	4	Micro	2	2	4	Meso	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2
Infrastructure failure	Technical				0	Micro	1	1	1	Meso	1	2	2	Meso	1	2	2				0	Meso	1	1	1	Micro	1	2	2	Micro	1	2	2

Fig. 3. The scores for Biogas of the causes of risk for the relevant stages. Entries in grey are not relevant at that stage. Source: Axon (2019). Stages 5 and 6 split into electricity (e) and pipelines (p) for distribution, and electrical devices (e) and heat (h) for use.



Cause of Risk	Category	Stage 1				Stage 2				Stage 3				Stage 4				Stage 5				Stage 6			
		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	1	1	1	Meso	2	1	2	Macro	1	3	3				0	Macro	1	1	1	Macro	2	1	2
Lack of access to capital	Economic	Micro	1	1	1	Meso	2	2	4	Macro	3	3	9				0	Meso	1	2	2	Micro	1	2	2
Unable to agree a price for licence or permits	Economic				0				0	Meso	1	2	2				0				0				0
Uncertain decommissioning costs	Economic				0	Micro	1	1	1	Micro	1	2	2				0	Micro	1	1	1	Micro	1	1	1
Price volatility	Economic				0	Macro	1	1	1	Macro	2	1	2				0	Macro	1	2	2	Meso	1	1	1
Difficult physical access	Environmental	Micro	1	1	1	Micro	1	1	1				0				0				0				0
Natural hazards	Environmental				0	Micro	1	2	2	Micro	1	2	2				0	Micro	1	2	2	Micro	1	2	2
Quality of fuel source	Environmental	Micro	3	1	3	Micro	1	1	1	Micro	3	2	6				0				0	Meso	1	1	1
Lack of water availability	Environmental				0	Micro	2	2	4	Micro	1	1	1				0				0				0
Lack of critical materials availability	Environmental				0				0	Macro	1	1	1				0				0	Macro	2	1	2
Weak technology transfer environment	Innovation				0	Meso	1	1	1	Macro	2	2	4				0	Macro	1	1	1	Macro	1	1	1
Lack of public subsidy	Innovation				0	Meso	1	1	1	Meso	2	2	4				0				0				0
Only marginal improvements likely	Innovation				0	Macro	2	1	2	Macro	1	3	3				0	Macro	3	1	3	Macro	3	2	6
Lack of material substitutability	Innovation				0				0	Macro	1	1	1				0				0	Macro	1	2	2
R&D capacity or capability does not match the challenge	Innovation				0	Macro	1	1	1	Macro	2	2	4				0	Macro	1	1	1	Macro	1	1	1
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Macro	3	2	6				0				0	Macro	3	1	3
Insufficient capacity to manufacture system components or conversion devices	Manufacturing				0	Macro	1	1	1	Macro	1	2	2				0	Macro	1	1	1	Macro	1	1	1
Insufficient capacity to construct sites	Manufacturing				0				0	Micro	1	2	2				0				0				0
Insufficient rate of infrastructure construction	Manufacturing				0	Meso	1	1	1	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1
Denial of permission to access sites	Political	Micro	2	1	2	Micro	1	2	2	Micro	1	2	2				0				0				0
Lack of social stability	Political	Meso	1	2	2				0				0				0				0				0
Changing policy or regulatory framework	Political	Meso	2	1	2	Meso	1	1	1	Meso	3	2	6				0	Meso	1	2	2	Macro	2	2	4
Poor institutional governance	Political	Meso	1	2	2				0				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	1	1	1				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0	Meso	2	1	2	Meso	1	2	2				0	Meso	1	1	1	Meso	2	1	2
Significant public concern	Political	Meso	2	1	2	Meso	2	1	2	Micro	2	1	2				0	Meso	1	1	1	Meso	3	2	6
Lack of basic education levels in the local workforce	Skills				0	Meso	1	1	1	Meso	1	1	1				0	Meso	1	2	2	Meso	1	1	1
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	2	1	2	Meso	2	2	4				0	Meso	1	2	2	Meso	3	1	3
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	2	3	6				0				0	Meso	3	1	3
Pollution event	Technical				0	Micro	3	1	3	Micro	3	2	6				0	Micro	3	2	6	Micro	3	1	3
Unable to neutralise waste at decommissioning	Technical				0	Micro	1	1	1	Micro	1	2	2				0	Micro	1	1	1	Micro	2	1	2
Specialist equipment unavailable	Technical	Micro	1	1	1	Micro	1	2	2	Macro	1	2	2				0				0				0
Operational failure	Technical	Micro	1	1	1	Micro	3	1	3	Micro	1	4	4				0	Micro	1	2	2	Micro	1	1	1
Infrastructure failure	Technical				0	Micro	1	1	1	Meso	1	2	2				0	Meso	1	1	1	Micro	1	1	1

Fig. 4. The scores for Bioliquids of the causes of risk for the relevant stages. Entries in grey are not relevant at that stage. Source: Axon (2019).

Although unlikely to occur, some farm tenancies may prohibit the deployment of facilities such as AD (Tranter et al., 2011) and if this were to occur it would stop a project completely. A risk more likely to occur is ‘Significant public concern’ through objections lodged to planning applications (Tranter et al., 2011; Clark and Roddy, 2012); this also occured for LFG (Brown and Maunder, 1994). ‘Changing policy and regulation’ is recognized as a risk. The uncertainty in support mechanisms (LCICG, 2012) led to fluctuating levels of subsidy compared with PV and wind (Tate et al., 2012), which Gowreesunker and Tassou (2016) observe as policy driving technology and not environmental considerations.

In the technical category, it is likely that a ‘Pollution event’ will occur (Röder, 2016). Biogas combustion cannot be CO_2 neutral even when using wastes. The AD process will generate fugitive methane emissions (Adams et al., 2015) including from the storage of digestate in open tanks and lagoons (Styles et al., 2016), which also have the potential to leak. An ‘Operational failure’ may occur, but should only lead to short-term disruption. Although fatalities are rare in the UK they do occur in biogas production (Burgherr and Hirschberg, 2014; Sovacool et al., 2016), likewise for other accidents (Sovacool et al., 2015).

4.1.2. Stage 4

At present, access to capital for a CCGT plant in the UK remains possible (modest risk). The Committee on Climate Change (CCC, 2015) suggests that costs should be judged on the whole-life including those of emissions, and not solely the LCOE, but Qadrdan et al. (2015) note that their modelling of scenarios with high levels of nuclear fission and offshore wind suggests that investment in CCGTs will be hard to justify. Barriers to on-farm combustion in a CHP unit have been noted, such as technical reliability and access to capital (Bywater, 2013; Foster et al., 2021).

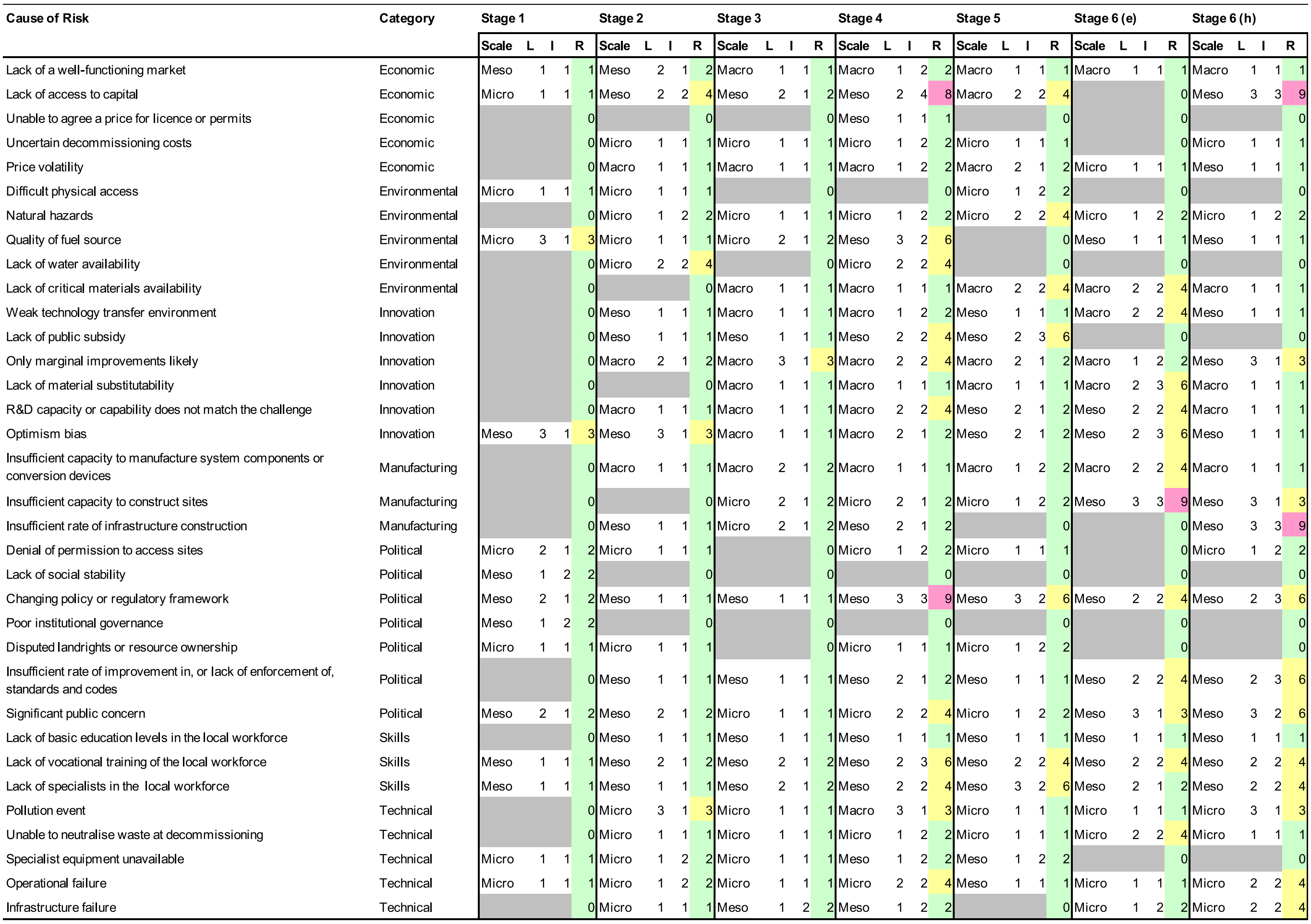
Improving CCGT efficiency is reducing the water requirements, Mielke et al. (2010) suggest a range of 114–795 $lMWh^{-1}$ and (Macknick et al., 2011) 15–1136 $lMWh^{-1}$ for the total consumed. These figures are low as there will be some additional requirement for the steam turbines in the thermal energy recovery system. Variation in gas composition, even within specification, has implications for the operation and performance of gas turbines (Abbott et al., 2012) which they consider may be exacerbated as a wider range of sources is imported in the future. Since we treat CO_2 emissions as a pollutant, the risk of a ‘Pollution event’ is in the highest category of risk.

4.2. Bioliquids

There is one high-level risk (at Stage 3), and 28 medium-level risks of which eight are notable.

4.2.1. Stage 1

The ‘Quality of fuel source’ is expected to vary from year to year and Acquaye et al. (2012) note the wide variations in potential CO_2 savings



Cause of Risk	Category	Stage 1				Stage 2				Stage 3				Stage 4				Stage 5				Stage 6 (e)				Stage 6 (h)			
		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	1	1	1	Meso	2	1	2	Macro	1	1	1	Macro	1	2	2	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Lack of access to capital	Economic	Micro	1	1	1	Meso	2	2	4	Meso	2	1	2	Meso	2	4	8	Macro	2	2	4				0	Meso	3	3	9
Unable to agree a price for licence or permits	Economic				0				0				0	Meso	1	1	1				0				0				0
Uncertain decommissioning costs	Economic				0	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1				0	Micro	1	1	1
Price volatility	Economic				0	Macro	1	1	1	Macro	1	1	1	Macro	1	2	2	Macro	2	1	2	Micro	1	1	1	Meso	1	1	1
Difficult physical access	Environmental	Micro	1	1	1	Micro	1	1	1				0				0	Micro	1	2	2				0				0
Natural hazards	Environmental				0	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	2	2	4	Micro	1	2	2	Micro	1	2	2
Quality of fuel source	Environmental	Micro	3	1	3	Micro	1	1	1	Micro	2	1	2	Meso	3	2	6				0	Meso	1	1	1	Meso	1	1	1
Lack of water availability	Environmental				0	Micro	2	2	4				0	Micro	2	2	4				0				0				0
Lack of critical materials availability	Environmental				0				0	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4	Macro	2	2	4	Macro	1	1	1
Weak technology transfer environment	Innovation				0	Meso	1	1	1	Macro	1	1	1	Macro	1	2	2	Meso	1	1	1	Macro	2	2	4	Meso	1	1	1
Lack of public subsidy	Innovation				0	Meso	1	1	1	Meso	1	1	1	Meso	2	2	4	Meso	2	3	6				0				0
Only marginal improvements likely	Innovation				0	Macro	2	1	2	Macro	3	1	3	Macro	2	2	4	Macro	2	1	2	Macro	1	2	2	Meso	3	1	3
Lack of material substitutability	Innovation				0				0	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	2	3	6	Macro	1	1	1
R&D capacity or capability does not match the challenge	Innovation				0	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4	Meso	2	1	2	Meso	2	2	4	Macro	1	1	1
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Macro	1	1	1	Macro	2	1	2	Meso	2	1	2	Meso	2	3	6	Meso	1	1	1
Insufficient capacity to manufacture system components or conversion devices	Manufacturing				0	Macro	1	1	1	Macro	2	1	2	Macro	1	1	1	Macro	1	2	2	Macro	2	2	4	Macro	1	1	1
Insufficient capacity to construct sites	Manufacturing				0				0	Micro	2	1	2	Micro	2	1	2	Micro	1	2	2	Meso	3	3	9	Meso	3	1	3
Insufficient rate of infrastructure construction	Manufacturing				0	Meso	1	1	1	Micro	2	1	2	Meso	2	1	2				0				0	Meso	3	3	9
Denial of permission to access sites	Political	Micro	2	1	2	Micro	1	1	1				0	Micro	1	2	2	Micro	1	1	1				0	Micro	1	2	2
Lack of social stability	Political	Meso	1	2	2				0				0				0				0				0				0
Changing policy or regulatory framework	Political	Meso	2	1	2	Meso	1	1	1	Meso	1	1	1	Meso	3	3	9	Meso	3	2	6	Meso	2	2	4	Meso	2	3	6
Poor institutional governance	Political	Meso	1	2	2				0				0				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	1	1	1				0	Micro	1	1	1	Micro	1	2	2				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2	Meso	1	1	1	Meso	2	2	4	Meso	2	3	6
Significant public concern	Political	Meso	2	1	2	Meso	2	1	2	Micro	1	1	1	Micro	2	2	4	Micro	1	2	2	Meso	3	1	3	Meso	3	2	6
Lack of basic education levels in the local workforce	Skills				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	2	1	2	Meso	2	1	2	Meso	2	3	6	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2	Meso	2	2	4	Meso	3	2	6	Meso	2	1	2	Meso	2	2	4
Pollution event	Technical				0	Micro	3	1	3	Micro	1	1	1	Macro	3	1	3	Micro	1	1	1	Micro	1	1	1	Micro	3	1	3
Unable to neutralise waste at decommissioning	Technical				0	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	2	2	4	Micro	1	1	1
Specialist equipment unavailable	Technical	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Meso	1	2	2	Meso	1	2	2				0				0
Operational failure	Technical	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	2	2	4	Meso	1	1	1	Micro	1	1	1	Micro	2	2	4
Infrastructure failure	Technical				0	Micro	1	1	1	Meso	1	2	2	Meso	1	2	2				0	Micro	1	2	2	Micro	2	2	4

Fig. 5. The scores for Biomass of the causes of risk for the relevant stages. Entries in grey are not relevant at that stage. Source: Axon (2019). Stage 6 splits into electrical devices (e) and heat (h) for use.

from different sources both of which add uncertainty to measuring the potential. The geographical location where crops are grown is an important factor (van Duren et al., 2015).

4.2.2. Stage 2

The quantity available may depend on fertilizer inputs (Firrisa et al., 2014), affecting the quality of the fuel source. The 'Lack of water availability' is not currently an issue in the UK, but will manifest periodically and may become more important in the future (Hammond and Li, 2016). The requirements for different sources varies widely (RAE, 2017).

Growing macro-algae whether inshore or farther out to sea requires a lease to use the seabed from The Crown Estate (Gegg and Wells, 2017) and a licence from the relevant maritime regulator, which may be denied. Each nation of the UK has a different regulator, but each requires potential seaweed farms to conduct an environmental impact assessment (Wood et al., 2017). Even though Roberts and Upham (2012) consider the impact assessment stage difficult to satisfy we assess this is unlikely to occur, but may cause short-term delays in starting a venture. The capital requirement for starting a seaweed farm, say, may pose a risk. The Royal Academy of Engineering note that standards and codes for categorising wastes and residues are needed to avoid distorting the market (RAE, 2017). 'Significant public concern' may arise connected with seaweed farms which may affect marine users (Roberts and Upham, 2012) and other communities (Rostan et al., 2022).

For the purposes of this study we classify ecosystem disturbance as an 'Operational failure' as it results from human decisions. Although difficult to quantify, disruption to ecosystem services does occur from growing energy crops (Styles et al., 2015) and land-use change is associated with increased emissions such as N_2O from fertilizer use (Whitaker et al., 2018).

4.2.3. Stage 3–4

The large scale of capital expenditure required is noted by Popp et al. (2014) and Hodgson et al. (2016). Specific issues affecting access to capital are demand uncertainty with Hammond et al. (2012) suggesting that a lack of investor confidence may arise due to competition with the electrification of transport. The established oil and gas 'majors' have the capability to design and operate biorefineries with Criscuolo and Menon (2015) classifying this as high-risk technology with high intensity capital requirements, presenting a high barrier to new entrants. We estimate that the risk of the 'Lack of access to capital' is likely to occur and that it could lead to a sustained but recoverable delay in projects.

The 'Quality of the fuel source' is the main risk in the environment category (Roberts and Upham, 2012; Hodgson et al., 2016), Popp et al. (2014) because meeting tight modern fuel specifications is harder with biofuels. Although variations in chemical or energy content can be accommodated, they may lower the efficiency of a biorefinery, needing additional processing steps.

Most elements of the process engineering required for biorefineries are well understood, but there is strong agreement that innovation is needed to address, for example: cost reduction through automation and intelligent systems (Goswami et al., 2022), lack of pilot studies (Pérez-Almada et al., 2023), process systems design (Katakojwala and Mohan, 2021), and advances in biology (Raj et al., 2022). Shortall et al. (2015) note the need for ongoing public subsidies and policy promoting a balanced approach to co-production of fuels and chemicals (Hodgson et al., 2016). Hodgson et al. also expressed concern about lack of co-operation between the key players, including traditional oil and gas processors and new entrants; we interpret this as a risk that the 'R&D capacity may not be able to meet the challenge'. These risks are moderate with only short-term effects.

'Changing policy and regulation' is noted as a significant cause of risk (Hodgson et al., 2016). The Royal Academy of Engineering (RAE, 2017) gives a concise overview of the liquid biofuels policy landscape and the (UKPIA, 2022) summarise the recent changes. Creating policy and regulation to support biofuels whilst markets and technology are still evolving has generated uncertainty and potential technical lock-in with a consequential loss of flexibility for biofuel development (Berti and Levidow, 2014). Poorly formed policy may lead to policy conflicts such as the effect on hydrogen fuel cell funding (Levidow and Papaioannou, 2014). We note that changes to policy and regulation will occur in the future, but are likely only to have short-term impacts.

A 'Pollution event' is likely, but may only cause short-term disruption. Proposed causes of pollution include increased NOx emissions (Hammond et al., 2012), eutrophication (Wang et al., 2013), alteration of sediment dynamics by seaweed farms (Wood et al., 2017), and effects on groundwater by spillages from refined products (Firth et al., 2014). Globally the accident frequency per TWh at biofuel facilities is similar to that of geothermal and solar, but the fatalities per TWh are lower (Sovacool et al., 2016). For the UK we evaluate the risk of 'Operational failure' to be the same at this stage as for oil and gas processing i.e. it is unlikely, but could close a site should a severe accident occur.

4.3. Biomass

There are five high-level risks, and 45 medium-level risks of which 10 are notable. Although at Stage 1 there are no significant risks, we note that the 'Quality of fuel source' will be variable from year to year which adds uncertainty into measuring the potential. For the Stage 3 (Conditioning), mechanical processing does not present any risks of note.

4.3.1. Stage 2

The 'Lack of access to capital' is a notable risk. The main problem is the return on investment compared with other uses of that land (Adams et al., 2011a) with many crops uneconomic (Warren et al., 2016), a need for new specialist harvesting machinery (Glithero et al., 2013b), and delayed cashflow as crops take several years to mature (Welfle et al., 2014). There is a source of risk in the technical category i.e. a 'Pollution event' caused by emissions from fertilizing energy crops (Drewer et al., 2017).

4.3.2. Stage 4

As the UK is phasing out the use of coal we only consider the direct combustion of biomass which, apart from subsidised power station applications, most likely uses grid-connected CHP plants, with a minority of projects powering a self-contained site where heat is distributed via a heat network.

The risk of a 'Lack of access to capital' is principally due to the uncertain rate of return on the investment (von Hellfeld et al., 2022) with several authors noting that subsidies are essential (Huang et al., 2017; McIlveen-Wright et al., 2013). Also noted is a *"lottery approach to grant funding"* for small organisations, charities, or Councils needing support for CHP purchase (Sinclair et al., 2015a), though Polzin et al. (2015) are of the view that feed-in tariffs (FIT) provide a better long-term signal than grants. Bassi et al. (2015) suggest that the risk perception of biomass is 'medium'. We interpret the essential nature of subsidies (whether by FIT or grant) as that the risk may occur but could halt a project entirely.

The 'Quality of the fuel source' is the main risk posed by the environment as biomass combustion properties vary (Forbes et al., 2014; Baxter et al., 2014; Al-Shemmeri et al., 2015; Röder and Thornley, 2018), affecting the CHP plant's efficiency. Seasonal variation (Adams et al., 2011a) will affect the efficacy of the unit or its economic performance. We estimate that the risk is likely to occur and may cause short-term disruption. For innovation, there is some evidence that public subsidy for technology development is required (Sinclair et al., 2015a) even though CHP is moderately mature.

Changes in the policy and regulatory landscape are well-recognized as a problem (Adams et al., 2011b; Connor et al., 2015; Sinclair et al., 2015b; Adams and Lindegaard, 2016; Levidow and Papaioannou, 2016). We conclude that this cause of risk is likely to occur and that the biomass system is less robust than some other fuels, so we consider that the disruption could be sustained though recoverable which places it in the highest category. There is also strong evidence that 'Significant public concern' will arise through objections to planning applications (Adams et al., 2011b; Sinclair et al., 2015b) but will have only a short-term effect.

Combusting (woody) biomass emits particulate matter and NOx (Olave et al., 2017), and is likely to lead to net CO_2 emissions across the supply chain which may exceed those of conventional gas (Brack, 2017). Whilst this risk will occur we expect it only to have an effect at the margins of normal operation. We note that the ash from biomass will be high in potassium and phosphorous, which although valuable cannot be discharged directly into the environment without treatment (decommissioning).

4.4. Distributing the final energy vector (Stage 5)

There are four final energy vectors to consider: electrons, molecules of gas (methane), molecules of liquid fuels (for vehicles), and (hot) water for heat networks. Each vector has its own infrastructure requirements and end-user devices or technologies. The distribution of hot water has to be localized, thus is considered as part of the end-user equipment requirements; although this is an anomaly, it can be handled within the constraints of the analytical framework.

The maturity of the electrical power industry suggests that innovation is only incremental (Bolton and Foxon, 2015), posing a high-level risk to progress towards the so-called 'smart grid' (Connor et al., 2018). Other risks and uncertainties (Kirschen, 2021) include deployment of ICT technologies (Hiteva and Watson, 2019) which challenge the power industry (Xenias et al., 2015). Risk from changing policy and regulation is significant (Connor et al., 2014), with Bolton and Foxon (2015) and Leal-Arcas et al. (2017) suggesting that governance is the key issue.

4.5. Using the final energy vector (Stage 6)

The final energy vectors are used by either electrical devices, vehicles, or heating systems (standalone or networked). Most causes of risk at this stage occur in the innovation and skills categories. The main issue for optimism bias is the rebound effect for energy efficiency (Sorrell, 2009, 2015). We evaluate both the likelihood high and impact to be significant but recoverable.

An 'Insufficient capacity to construct sites' i.e. the replacement of energy inefficient buildings by refurbishment or demolition and new build is assessed as a high-level risk. The demolition rate (unadjusted for stock age) is about 0.04 % p.a. (DCLG, 2017). As roughly 20 % of the stock was built before 1919, 55 % between 1920 and 1979, and 25 % 1980 or later (MHCLG, 2018) less than 2 % of older dwellings will be demolished over the next 30 years, assuming that only pre-1980 stock is demolished. This means that 98 % of the dwellings in 2050 are extant in 2023. An 'Insufficient rate of improvement in, or lack of enforcement of, standards and codes' has greater impact for buildings, though Roberts and Axon (2022) show that the volume housebuilders do have the financial capacity to improve the energy efficiency of new-build homes.

The efficiency of modern internal combustion engines is dependent on tight fuel specifications which are harder for biofuels to meet (Bergthorson and Thomson, 2015). For liquid fuel powered vehicles there is by definition a 'Pollution event' at every use, with attendant risks to human health (Smith et al., 2013; Brand, 2016). There is evidence that some air passengers are not comfortable with aeroplanes using a biogenic fuel rather than kerosene (Filimonau and Högström, 2017).

Surveys of evidence and practice reveal a complicated technical, regulatory, and policy landscape for heat (Hanna et al., 2016) which in part explains why relatively little progress has been made in the decarbonisation of the supply of thermal energy. R&D and manufacturing capacities for the heat sector in the UK are flagged as notable risks.

4.6. Skills

A large-scale survey of stakeholders in the bio-based economy (Hodgson et al., 2016) found a broad lack of technical level skills, with Tranter et al. (2011) noting this for the installation and operation of AD. For biofuel processing, surveying by Hammond et al. (2012) recorded the lack of high-level biofuel expertise particularly in biochemistry, chemistry, and automotive engineering, noting that industry instability made it unattractive to skilled people of all levels.

At the distribution stage, the provision of low-carbon heat devices, services, and infrastructure is recognized as having skills shortages (Wade et al., 2016). Concerns have been raised about high-level skills gaps for district heating (BRE et al., 2013; LCICG, 2016).

4.7. Distribution of risk in the supply chains, and comparison with other fuels

The risk distribution along the biofuel supply chains is shown in Table 2, with the cumulative scores in Fig. 6. The conditioning and conversion stages have the highest scores for biofuels, but for other fuels the most risky stage is exploitation. Evidently for biofuels the exploitation stage which involves gathering crops, though certainly not risk-free, involves less risk than stage 2 in other supply chains. Five of the eight risks in the high scoring category are encountered in the biomass (solids) supply chain, which also has the highest total risk score (Table 2). The normalised total risk scores for all fuels are given in the appendix (Table A1) showing that the biofuels all attract more risk than might be commonly considered. They are the three most risky renewables, with biomass and biogas landing in the second most risky group behind some fossil fuels and nuclear.

In Fig. 7 we note that the plots – (a) and (d) – for electricity generation are similar as expected due to shared instructure and technology, but for heat – (b) and (e) – the story differs. The on-site heat delivered by biomass is mostly CHP, whilst for biogas this will be individual home heating. The area of each graph is proportional to the total (absolute) risk score.

Table 2
The absolute scores for the three biofuels at each stage. The normalised risk score is only generated at the final step to minimise rounding errors. The risk score is calculated from Figs. 3–5.

Stage	Risk score (abs)			Average renewables†	Average (all fuels)†
	Biogas	Bioliquids	Biomass		
Explore	26	24	24	27	40
Exploit	44	48	45	87	93
Condition	71	94	37	18	34
Convert	84	——	92	16	46
Distribute*	17	17	4	6	16
Use*	15	26	82	19	16
Total	**257**	**209**	**284**	**173**	**245**

† Source: Axon (2019).
* Stage scores account for shared infrastructure and use types.

Table 3 ranks the causes of risk starting with the highest scoring, and compares scores and rankings with fossil fuels, and all fuels. We note that for all fuels all seven categories of risk are represented at teast once in the top ten places. The even spread of categories through the ranking list suggests that the method for risk discovery and evaluation is unbiased.

Each biofuel chain is compared in Table 3 with the fossil fuel chain it nominally replaces. The values highlighted in orange indicate where the bioenergy alternative has a higher or equal score for that cause of risk. In understanding energy security as the low-risk (dependable) meeting of energy needs within the economy (Axon and Darton, 2021c), we would expect that introducing new fuel sources would reduce risk in the energy economy. Table 3 shows that this is largely true for biogas and bioliquids, but not for biomass; replacing coal with biomass (solids) fails to reduce risk for two thirds of the causes of risk. In common with all fuels, the two most siginificant causes of risk are 'Changing policy or regulatory framework' and 'Lack of access to capital'. However, for some other causes of risk the incumbent fuels enjoy an advantage. For example for fossil fuels, the 'Lack of vocational training of the local workforce' is ranked ninth, whereas for biofuels it is ranked third in importance; 'Optimism bias' is ranked 15th for fossil fuels but for the bioenergy routes it is ranked fifth. The same observation may be made for 'R&D capacity or capability does not match the challenge' (17th and 10th), 'Insufficient rate of improvement in, or lack of enforcement of, standards and codes' (20th and 13th) and 'Lack of public subsidy' (32nd and 17th). For all these risks it is conjectured that the fossil fuel industry, with long operating experience, has been able to take measures to mitigate the risks. Promoting the use of biofuels to replace their fossil equivalents will require these risks to be addressed in the new supply chains, and failure to do this adequately may contribute to the continuing limited large-scale deployment of bioenergy production and use in the UK.

It is also interesting to note causes of risk which rank significantly higher for fossil fuels, suggesting an advantage for biofuels. These are 'Pollution event' (ranked first and fourth, respectively), 'Significant public concern' (third and sixth), 'Only marginal improvements likely' (fifth and eighth), 'Natural Hazards' (seventh and 14th), 'Unable to neutralise waste at decommissioning' (10th and 18th). These rankings demonstrate the comparatively smaller environmental risks of biofuels and their greater social acceptability, and scope for further improvements offered by a young industry.

'Quality of fuel source', for all biofuels, currently ranks 12th out of 34 – towards the top but not one of the most important risks. But if the demand for biofuel rises to a level that cannot be met by current feedstocks, less suitable feedstocks will then have to be used. If actions suggested by the (IEA, 2023b) are either not taken or not effective, then the feedstocks that are available will no longer be a good fit to the industry's processing capability. The level of risk 'Quality of fuel source' could then become high, hindering growth of the market. Associated causes of risk such as 'R&D capacity or capability does not match the challenge', and 'Price volatility', may also become more important. Through its transparency, the methodology lends itself to reappraisal of risk in the light of changing circumstances.

At the bottom of Table 3 are five causes of risk with low scores for biofuels. These are 'Difficult physical access' (ranked 11th and 30th), 'Unable to agree a price for licence or permits' (21st and 32nd) and three political risks – 'Disputed landrights or resource ownership' (24th and 31st), 'Lack of social stability' (23rd and 33rd) and 'Poor institutional governance' (25th and 34th). These perhaps demonstrate advantages of supply chains being within the UK land border, given the country's relatively strong position with regard to legal and financial frameworks, and governance.

Characteristics of the three biofuels revealed by this risk analysis are summarised in Table 4. Note the difference in the risk score for each of the three biofuels, and that the highest-scoring category of cause of risk

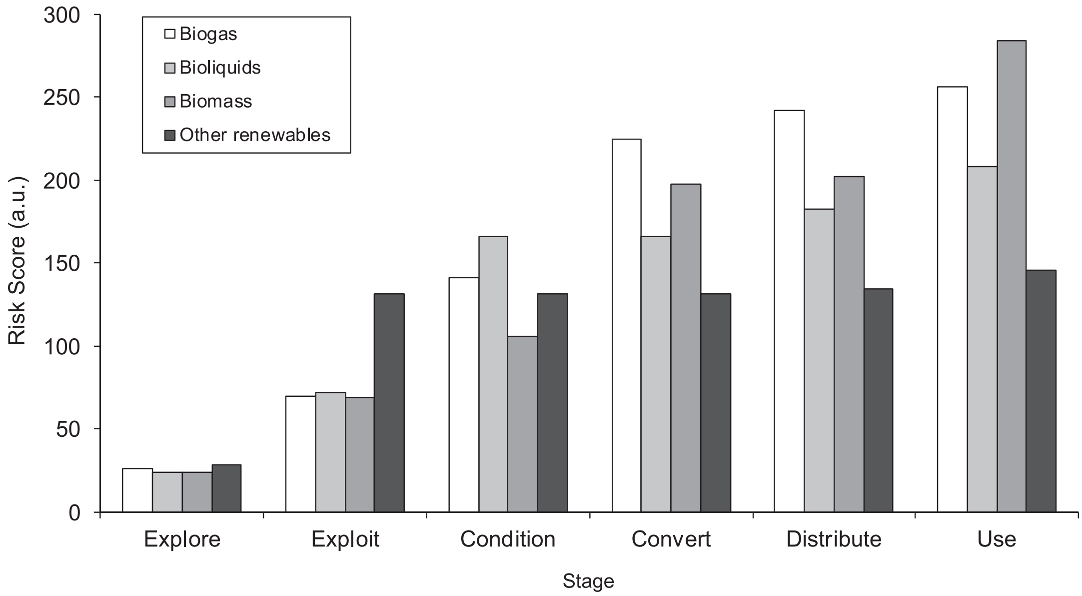


Fig. 6. Comparison of the cumulative absolute risks scores for the bioenergy family and the average for all renewables. Data for all renewables: Axon (2019).

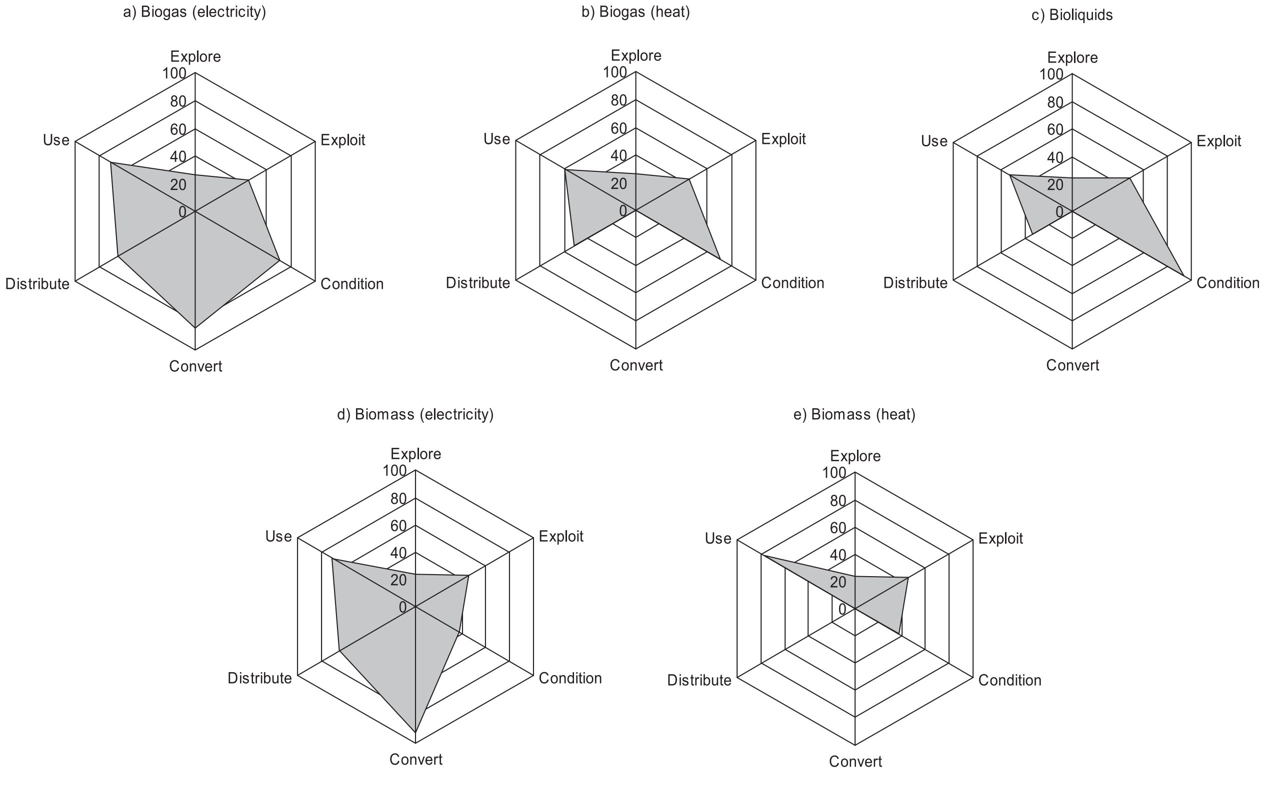


Fig. 7. Radar plots of absolute risks scores for the bioenergy family and the use of the final energy vector.

is technical for biogas, innovation for bioliquid and political for biomass.

4.8. Limitations of the method

Our method, which aims to identify all the risks in a fuel supply chain, using published literature as the data source has some limitations that must be recognized for a balanced appreciation of the results. A fully comprehensive analysis could be time-consuming, though modern literature databases can be quickly and efficiently searched, and it has proved to be feasible at low cost and within a reasonable time-frame. The various supply chains display many similarities, so elements of the risk analysis will repeat, speeding the process. The method assumes that for the geographical area considered (a nation) the energy economy is sufficiently homogeneous for the analysis with its risks to be applicable everywhere. For large and diverse jurisdictions it may be necessary to consider constituent parts separately.

The method assumes that all relevant risks will have been sufficiently well recorded and described to enable the evaluation. Fortunately the literature on bioenergy, both peer-reviewed and grey, is voluminous, so it is unlikely that significant risks will have been omitted in our case

Table 3
Risk scores for each biofuel chain compared with the fossil fuel chain it nominally replaces. Risk score differences highlighted in orange indicate where the risk is ***not*** reduced by introducing biofuel. Note: BF = BioFuels, FF = Fossil Fuels.

The risk categories are colour-coded: Economic Environmental Innovation Manufacturing Political Skills Technical

Cause of Risk	Risk Score (by Cause of Risk)												Rank		
	Biomass	Coal	Diff	Biogas	Gas	Diff	Bioliquids	Oil	Diff	All BF	All FF	Diff	All FF	All BF	All Fuels †
Changing policy or regulatory framework	29	21	8	30	29	1	15	16	-1	74	66	8	4	1	2
Lack of access to capital	28	27	1	21	33	-12	18	29	-11	67	89	-22	2	2	1
Lack of vocational training of the local workforce	23	15	8	25	27	-2	12	16	-4	60	58	2	9	3	4
Pollution event	12	24	-12	27	35	-8	18	33	-15	57	92	-35	1	4	8
Optimism bias	18	13	5	21	18	3	15	10	5	54	41	13	15	5	7
Significant public concern	20	19	1	19	28	-9	13	27	-14	52	74	-22	3	6	3
Lack of specialists in the local workforce	20	17	3	20	27	-7	11	16	-5	51	60	-9	6	7	6
Only marginal improvements likely	16	16	0	19	24	-5	14	23	-9	49	63	-14	5	8	11
Operational failure	14	12	2	17	26	-9	11	21	-10	42	59	-17	8	9	9
R&D capacity or capability does not match the challenge	13	14	-1	19	19	0	7	6	1	39	39	0	17	10	14
Insufficient capacity to construct sites	18	16	2	19	24	-5	2	8	-6	39	48	-9	12	11	5
Quality of fuel source	14	13	1	13	18	-5	11	17	-6	38	48	-10	13	12	17
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	15	10	5	16	18	-2	7	8	-1	38	36	2	20	13	18
Natural hazards	13	11	2	14	27	-13	8	22	-14	35	60	-25	7	14	10
Lack of a well-functioning market	9	10	-1	15	18	-3	9	13	-4	33	41	-8	16	15	15
Insufficient capacity to manufacture system components or conversion devices	11	10	1	16	20	-4	5	9	-4	32	39	-7	18	16	12
Lack of public subsidy	12	9	3	13	11	2	5	4	1	30	24	6	32	17	16
Unable to neutralise waste at decommissioning	10	17	-7	14	24	-10	6	17	-11	30	58	-28	10	18	13
Weak technology transfer environment	10	13	-3	12	14	-2	7	8	-1	29	35	-6	22	19	19
Infrastructure failure	11	7	4	10	12	-2	5	10	-5	26	29	-3	27	20	28
Price volatility	8	13	-5	11	16	-5	6	15	-9	25	44	-19	14	21	20
Lack of critical materials availability	11	10	1	11	12	-1	3	6	-3	25	28	-3	29	22	23
Denial of permission to access sites	8	7	1	11	10	1	6	12	-6	25	29	-4	28	23	22
Lack of water availability	8	12	-4	11	9	2	5	5	0	24	26	-2	31	24	32
Lack of material substitutability	10	9	1	11	12	-1	3	7	-4	24	28	-4	30	25	21
Insufficient rate of infrastructure construction	14	5	9	6	9	-3	4	10	-6	24	24	0	33	26	25
Specialist equipment unavailable	8	8	0	9	13	-4	5	9	-4	22	30	-8	26	27	26
Uncertain decommissioning costs	6	8	-2	7	15	-8	5	14	-9	18	37	-19	19	28	27
Lack of basic education levels in the local workforce	6	5	1	7	8	-1	5	7	-2	18	20	-2	34	29	31
Difficult physical access	4	9	-5	10	22	-12	2	19	-17	16	50	-34	11	30	24
Disputed landrights or resource ownership	5	8	-3	7	14	-7	2	11	-9	14	33	-19	24	31	30
Unable to agree a price for licence or permits	1	15	-14	4	12	-8	2	9	-7	7	36	-29	21	32	29
Lack of social stability	2	2	0	2	16	-14	2	16	-14	6	34	-28	23	33	33
Poor institutional governance	2	2	0	2	15	-13	2	15	-13	6	32	-26	25	34	34

†Source: (Axon and Darton, 2021b).

study. For other nations with a similar energy economy we would expect to obtain similar results; but some nations lack the relevant published information, hindering this type of assessment. Reliance on publications introduces the question of bias, conscious and unconscious, both in the literature and of the analysts. This could lead to risks being incorrectly evaluated. To counter this we rely on transparency of the method and scoring, and on the peer-review of literature sources. Critical reading of the literature can identify bias, particularly if there are multiple sources to compare. It is certainly the case that risks in areas like manufacturing and innovation receive much less attention from commentators than say political risks, so adhering to a common scoring protocol across risk categories is important to avoid importing bias into the assessment. Statistical techniques can check for self-consistency, the tendency to rate say, economic risks more highly than environmental risks or vice versa. An expert workshop was organized to consider and benchmark our UK case study, and this has been reported (Axon and Darton, 2021b). Stakeholder consultation is always useful to illuminate issues and identify gaps.

Another limitation is that the method is descriptive not predictive – it aims to produce a comprehensive snapshot of the energy economy and its supply chains as described in the literature of the moment. We used the analysis to examine future energy scenarios to envision how UK electricity generation risk profiles might change up to 2050 (Axon and Darton, 2023), but the assumption was that the risk characteristics of particular fuels did not change appreciably over the period. This assumption was reasonable because the method is insensitive to small scoring errors (Axon and Darton, 2021b). Updating the analysis is managed by examining if new information or literature changes the existing score.

Our method emphasizes the need to evaluate all of the risks approximately rather than only some risks accurately. This implies making risk evaluations with a certain granularity (allowable lack of accuracy), by using the 3 × 4 matrix for likelihood (L) and impact (I) with its restricted scoring scale (Section 3.2). The worst-case uncertainty in the estimates of the likelihood and impact scores has been calculated (Axon and Darton, 2021b) and shown to be sufficiently small not to shift any fuel source into a different cluster in the ranking of all fuels; the degree of granularity represented by the 3 × 4 Likelihood-Impact matrix therefore permits a useful ranking of risks, and is not a limitation in the analysis.

Table 4
Summary of characteristics of the three biofuels.

Characteristic	Biogas	Bioliquids	Biomass
Fuel type	Renewable	Renewable	Renewable
Risk group[†]	Biogas, Biomass, Coal, Thermal (geological).	Bioliquids, Demand Reduction, Ocean (tidal), Ocean (wave), Waste.	Biogas, Biomass, Coal, Thermal (geological).
Normalised risk score [†]	61	48	63
Relative position [†]	8 / 19 most risky	9 / 19 most risky	6 / 19 most risky
High-level risks (number)	2	1	5
Medium-level risks (number)	59	28	45
High-level risks	Insufficient capacity to construct sites (Stage 6), Pollution event (Stage 4).	Lack of access to capital (Stage 3).	Lack of access to capital (Stage 4 & 6), Insufficient capacity to construct sites (Stage 6), Insufficient rate of infrastructure construction (Stage 6), Changing policy or regulatory framework (Stage 4).
Riskiest category	Technical	Innovation	Political
Riskiest stage	Stage 4: convert	Stage 3–4: condition / convert	Stage 4: convert
Most significant cause of risk	Changing policy or regulatory framework (Political)	Lack of access to capital (Economic), Pollution event (Technical).	Changing policy or regulatory framework (Political)

[†] Source: (Axon and Darton (2021a)).

As the screening method considers one supply chain at a time, systemic risks can be difficult to identify since such risks involve interactions across the supply chains of different fuels. The common occurrence of a particular cause of risk across multiple fuels at multiple stages could be an indication of systemic risk, but this remains conjectural (Axon and Darton, 2021b). Even more difficult to account for is systemic risk occurring between fuel supply chains and those for other commodities such as food or water. The experience of the EU in attempting to promote biofuel production has shown the importance of this Energy-Water-Food nexus, but it requires a fully comprehensive method to capture the complexity (Keairns et al., 2016).

5. Conclusions

If biofuels are to play a useful role in reducing carbon emissions, with rapid and widespread deployment, there is a need to understand what the main risks of supply chain disruption are, where they occur, their significance, and their causes. However, a method for the systematic identification and evaluation of risk in (bio)fuel supply chains has previously been lacking. A rich diversity of biomass sources can be converted into biofuels through a wide range of processes. The product, depending on its type and specification, could serve a variety of markets and applications. Some of these processing routes bifurcate, competing in different markets using the same biomass resource. The wide range of options and the variety of impacts involved must be considered against a background of rapidly changing technologies and markets. This complex picture presents a significant challenge in the formulation of commercial strategy and bioenergy policy.

We present a method for the comprehensive evaluation of risk in biofuel supply chains using the wide range of published literature as data source. Our data-driven approach exposes, categorises, and quantifies risk, providing information to help commercial development and target policy at reducing the barriers to biofuel deployment. In the UK case study, risk is found throughout the supply chains for the three biofuels, but there are distinct differences between them. Five of the eight risks in the high-scoring category are encountered in the biomass (solids) supply chain, which has the highest total risk score. Our study assigns biomass (solids) a similar risk score to coal, with biogas being slightly less risky, and bioliquids less risky still. Replacing coal with biomass (solids) fails to reduce risk for two thirds of the causes of risk. We note that the highest risk scores for biofuels occur at the conditioning and conversion stage, whereas for other fuels, renewable or not, the most risky stage is exploitation. The high-level risks with biofuels arise from the scale and complexity of processing, and thus the significant investment, required to create the volume and quality of product suitable to replace current fossil alternatives. The process plant required for biofuels is similar to that for fossil fuels, attracting as much risk as some non-renewables along the supply chain and more than other renewables. The most significant individual cause of risk is found to be ‘Changing policy or regulatory framework’ (in the Political category). The second and third most significant are the ‘Lack of access to capital’ (Economic) and ‘Lack of vocational training of the local workforce’ (Skills), respectively. A stable policy and regulatory framework, and good availability of skilled personnel are essential to encourage the investment that bioenergy needs. Levels of ‘Optimism bias’ in the biofuel industry are high – it is the fifth highest ranking risk – leading to unrealistic expectations from complex technologies and dubious claims about the quantity of resource available.

Our analysis shows that the environmental risks of biofuels are smaller than for fossil fuels, their social acceptability is greater, and there is more scope for innovation which could lead to further improvements. Innovation, however, also presents a challenge, since the various feedstocks, products and processes offer many niches requiring investment and innovation, making economic returns more difficult and impeding the establishment of a biofuel industry. There is an opportunity cost in pursuing new technologies at the expense of existing ones needing roll-out. Subsidies and effort need to be focused on those applications that would be hard to decarbonise in other ways, could command a premium, or could become commercially viable. At present there is no clear business case for large-scale combustion of (imported) biomass in the UK which depends heavily on subsidy and thus on the policy landscape, contributing to the risks noted.

Certain types of risk urgently need more research, particularly in view of the importance of the transition to lower-carbon energy systems. These include risks in the categories ‘manufacturing’ and ‘innovation’, and systemic risks in general.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

C.J. Axon: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **R.C. Darton:** Conceptualization, Investigation, Writing – review & editing.

Declaration of competing interest

None.

Appendix A. Appendix

Table A1
Ranked list of the 19 fuels (unweighted for the availability of each fuel), together with the number of high-level risks associated with each fuel. The grouping of the fuels is denoted. Source: Axon (2019); Axon and Darton (2021a).

Fuel	Fuel type	Normalised risk score (a.u.)	No. high-level risks
Gas (unconventional)	Non-renewable	100	12
Gas	Non-renewable	99	11
Oil	Non-renewable	98	10
Nuclear (fission)	Non-renewable	94	17
Thermal (geological)	Non-renewable	80	11
Biomass (solids)	**Renewable**	**65**	**5**
Coal	Non-renewable	65	6
Biogas	**Renewable**	**61**	**2**
Bioliquids	**Renewable**	**48**	**1**
Ocean (wave)	Renewable	47	9
Demand Reduction	Non-renewable	45	5
Waste	Non-renewable	43	3
Ocean (tidal)	Renewable	42	6
Thermal (low temperature)	Renewable	37	4
Wind (offshore)	Renewable	34	4
Wind (onshore)	Renewable	32	5
Hydro	Renewable	31	5
Solar (electric)	Renewable	25	3
Solar (thermal, water)	Renewable	20	1

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