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A Method for Assessing the Risks to Sustainability Posed by Process Operations

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ABSTRACT

We present a framework for assessing the risks to sustainability posed by any given set of processes. The objective is to improve sustainability by enabling better decision-making in policy and business contexts. The framework can be applied to any system of processes where available information supports discovery and quantification of sustainability-risk, defined as risk to the ability of future generations to meet their needs. Processes are screened to identify sustainability-risks, which are scored on a common scale to avoid arbitrary weighting factors. The method yields an overall risk score for the system, and an analysis of where and how sustainability-risk arises. We demonstrate the method by applying it to the system that provides for the UK's production and use of liquid biofuels. A set of 18 distinct causes of risk is discovered, and impacts are assessed by triple-bottom line accounting. The innovation risk *optimism bias* is the highest-scoring cause of risk, followed by *price volatility* associated with competition between markets for bio-feedstocks. In this case, the wide variety of risk types and severity, and scale of action, suggests that promoting sustainability requires a tailored response to address specific risks.

1 | Introduction

According to The Brundtland Commission (United Nations 1987) strategies for achieving sustainable development need to integrate economic and ecological considerations in decision-making, taking a long-term and broad view of the potential impacts resulting from choices made. An appropriate way of assessing the sustainability of a system comprising a number of processes is by considering systematically all those processes and their impacts. Using sets of indicators to measure sustainability impacts is a well-established method (Dalal-Clayton and Sadler 2014), having its origin perhaps in the prior development of Environmental Impact Assessment (EIA). In EIA the environmental impact of a project, or manufacturing operation, say, is assessed by making an inventory of the processes, products and emissions, and quantifying with numerical indicators the environmental impact of each one (Morgan 2012). A similar procedure of inventorisation and quantification underpins Life Cycle Assessment though this technique has now been developed far beyond its original purpose of identifying environmental burdens (McManus and Taylor 2015).

In the field of sustainability strategy, it is recognised that the correct choice of indicator sets is crucial to guiding decision-making that reduces negative impacts on sustainability, and there has been much discussion of how such indicator sets might be chosen (Kwatra et al. 2020). Using triple bottom line accounting and measuring each impact in terms appropriate to the nature of the impact, the Process Analysis Method (PAM) yields a set of indicators characterising the sustainability of the system (Chee Tahir and Darton 2010). The PAM aims to be comprehensive by identifying *all* significant impacts of system processes and linking indicators through those impacts to the activities that cause them. The PAM thus links cause and effect and in this it differs from methods using standard lists of indicators, which can lead to the inadvertent neglect of important issues

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in particular cases. The PAM stresses the importance of transparency so that the assessment can easily be checked, modified and corrected, and of involving stakeholders (Darton 2017). Stakeholder input adds richness, depth, and authenticity, both in suggesting the relative importance of different issues, and in matters key to the analysis, such as what might be considered a sustainable outcome and what should be included or excluded when choosing the system boundary.

The final indicator set for assessing the impact of a system on sustainability is often found to consist of about 30–60 individual indicators (Kwatra et al. 2020). Typically, the set includes both negative and positive impacts on sustainability, characterizing a wide variety of issues. To be useful in guiding decision-making, it is necessary to weight these various impacts, according to their perceived importance. The inclusion of both positive and negative effects requires trade-offs, the value of benefits being weighed against the disadvantages of disbenefits. Whilst the indicator set should represent a stated view of what is meant by sustainability, it is by no means clear how weighting factors and trade-offs should be chosen to be consistent with any particular stated view. Stakeholders can legitimately differ widely in assessing weighting factors, providing a source of variability in assessments of the same system (Ekener et al. 2018; Gan et al. 2017). This difficulty is common to LCA and other multi-indicator methods of system assessment and may be described as the 'indicator-weighting problem'.

Most assessments of system sustainability, like the PAM, do not account for risk. Operation of the system under investigation is taken to be describable in terms of impacts that *do* or *will* occur, neglecting risk events that occur infrequently, or may not yet have occurred at all. The resulting analysis will focus on short-term predictable effects rather than on the longer-term changes important for sustainability (Eckert et al. 2022). Uncertainty about whether particular impacts should be included, and if so, how, is an additional reason for variability between different analysts' assessments of the same system.

Sustainability shares some features in common with energy security (Axon and Darton 2021a), both concepts describing a desirable property of an economy in the sense of its definition as 'the management or administration of the material resources of a community, discipline, or other organized body' (Oxford English Dictionary). Energy security is the low-risk (dependable) meeting of energy needs within an economy (Axon and Darton 2021a), whereas sustainability requires that needs be met in a way that does not compromise the ability of future generations to meet their own needs (United Nations 1987). Measuring the risk to the energy security of an economy means assessing the *dependability* of the system that supplies energy to meet demand. The PAM approach to system analysis has been developed into a Risk Assessment Method (RAM) (Axon 2019) to quantify the risk of disruption in different fuel supply chains, indicating their dependability (Axon and Darton 2021b, 2021c).

Our objective is to create a novel method, without arbitrary weighting factors, that assesses the level of risk that operating a system of processes poses to sustainability. The proposed Sustainability-Risk Assessment Method (SRAM) comprehensively identifies these risks. It is not however a full sustainability analysis, as it identifies only potential negative impacts on sustainability (i.e., the risks) and *not* the benefits. A separate procedure is needed to identify the positive benefits which could then be weighed against the risks. We do not deal with this trade-off here. It will be shown that identifying and quantifying risks to sustainability itself already yields important information to guide decision-making that avoids or reduces these risks, in accordance with Brundtland's objective.

2 | Review of Sustainability-Risk

We use the Oxford Dictionaries definition of risk as '(Exposure to) the possibility of loss, injury, or other adverse or unwelcome circumstance'. It is a feature of risk that estimating the likelihood of a particular 'loss, injury etc.' incurs the uncertainty of *any* prediction about the future. The risk may describe an outcome whose likelihood varies from very unlikely to almost certain. (Krysiak 2009), recognising the importance of risk and uncertainty in the sustainability discourse, defined sustainability as 'the obligation to limit the risk of harming future individuals', and suggested using tools from risk management to minimise this risk. However, quantification of risk rarely features in attempts to measure sustainability, despite early recognition of the importance of risk concepts and the potential for risk management to guide strategies for improving sustainability (e.g., Cawdery and Marshall 1989; Dovers and Handmer 1992; O'Riordan and Rayner 1991). As Eckert et al. (2022) remark, 'an explicit link between sustainability expressed in a systemic framework and risk assessment/mitigation is currently lacking'. In consequence, sustainability analysis has been focused on future impacts that can be plausibly extrapolated from the present (Eckert et al. 2022). Such a bias emphasises elements thought to be predictable, such as in technical and environmental systems that can be modelled, neglecting areas where the future is less predictable, involving societal change, for example, or where the time scale is long. Possible negative impacts may also be neglected as a result of optimism bias—judging that their likelihood or impact is less than it really is, or through failing to recognise discontinuous change (Winn et al. 2011).

Risk management techniques have been used to address elements of some clearly defined problems with implications for sustainability; for example to identify strategies to reduce human vulnerability to climate change (Heltberg et al. 2009), to measure and improve the sustainability of civil engineering projects (Fernández-Sánchez and Rodríguez-López 2010), to identify and manage risk in sustainable smart city governance (Ullah et al. 2021), to identify causes of risk in fresh-water ecosystems as underpinning for policy and management of water resources (Bănăduc et al. 2022), cyber-security (Erdem and Özdemir 2025), integrating impact assessment by LCA with risk discovery through Failure Mode and Effect Analysis to promote sustainable manufacturing (Schneider et al. 2024) and to develop better policy for promoting bioenergy projects (Welfle et al. 2023). Adapting risk assessments to address sustainability has been discussed by (Wassénius and Crona 2022).

There is a significant volume of literature on sustainable supply chains (SSC), and this is instructive because it illustrates the importance of clarity in defining sustainability which is often lacking in work on corporate sustainability (Hockerts and Searcy 2023). Whilst impacts on the three domains of sustainability (economic, environmental, human/social) are sometimes used to identify risks in the supply chain (Ahi and Searcy 2013), it seems that the sustainability deemed at risk in much SSC literature is of the supply chain itself, or of the businesses that participate in it. Hofmann et al. (2014) describe a standpoint where 'sustainability issues materialize and create losses to focal firms'. Similarly Schulte and Hallstedt (2018) define risks to sustainability as '… risks that are due to an organisation's contribution or counteraction to society's transition towards strategic sustainable development'. Such risks arise from the adoption of sustainable practices, are additional to 'normal' or 'typical' risks and can cause damage to an organisation when a risk event is triggered. They must be included in the risk management of the organisation.

We define 'sustainability-risk' as the risk to the ability of future generations to meet their own needs; such risks arise as consequences of human activities or natural causes. With this definition, meeting the needs of future generations is the central concern, rather than the undisturbed operation of organisations or structures that meet current needs. The sustainability-risk posed by any particular process operation is assessed by its impact on this future capability to meet needs, taking a forward look at risks.

This definition of sustainability-risk has an important consequence. The difference between sustainability assessment and sustainability-risk assessment is that the former (using PAM or any other method) determines that an indicator describes an important element of the sustainability of the system under examination. But quantifying the *sustainability-risk* captures the importance of that indicator. Sustainability-risk therefore offers a route to addressing the indicator-weighting problem.

Identifying sustainability-risk presents a challenge, but risk discovery and quantification in general is a well-known problem with much literature describing both theory and practice with a very wide range of applications (Aven and Renn 2018; Baybutt 2018; Duijm 2015; ISO 2019; Waters 2011). Assessing the degree of risk—quantification—relies on interpreting information about past performance and similar or analogous situations to suggest the impact and likelihood of an identified risk.

3 | Method

We adopt the principles of the PAM (Darton 2017) for assessing sustainability and the RAM (Axon 2019) for assessing energy security, and apply them to the challenge of framing and quantifying sustainability-risk.

The SRAM is designed to analyse a generic system as shown in Figure 1. Within an economy, a system uses energy and material resources to produce beneficial outputs of goods and/or services. At the same time, 'waste' energy and materials are produced and require suitable disposal. An input of Human/Social capital in Figure 1 reminds us that this is also needed for the system to function. A notional boundary can be drawn around this system to include all system processes, with resource inputs and outputs crossing the boundary. It is the risks that operation of this system presents to sustainability that we wish to identify and quantify.

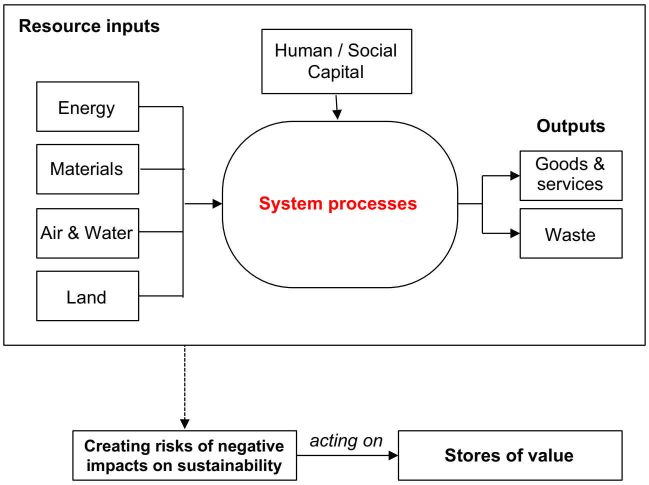


FIGURE 1 | Generic system overview.

The provision of goods and services often involves a supply chain or a supply network, and the system shown in Figure 1 can comprise the whole of it, or a part, as defined by an appropriate boundary. Figure 1 was inspired by representations of the law of conservation of mass and the working of heat engines and is intended here to show the links between main features of the generic system. Associated with the flows of resources shown in Figure 1 are flows of money. These are omitted in Figure 1 but must be considered when sustainability-risks are addressed. Systems that we might analyze in this way could provide, for example, manufactured goods, or products from agriculture or forestry, or services like healthcare, education or transportation.

Application of the method is outlined in Figure 2. In the first step, an overview of the system processes is drawn up, activities being grouped, if necessary, into the minimum number of processes that adequately represent the system giving the granularity appropriate for the analysis. It is helpful to create diagrams of the operation showing links between processes together with their inputs and outputs. In step 2 an explicit working definition of sustainability is developed to describe what constitutes a sustainable outcome in the context of the particular application; the statement of application-relevant sustainable outcomes provides clarity and helps to ensure completeness and consistency in the analysis.

The system boundary is defined in step 3 together with protocols for how any transfers of resources or impacts across the boundary will be treated—a common requirement of system analysis techniques, such as Life Cycle Assessment. In step 4, the sustainability-risk framework by which risks are discovered (detailed below) is devised and applied. Verifying and modifying the analysis in step 5 takes account of input from stakeholder consultation whenever possible; this step may require change to individual risk assessments, or even to the overview and definitions. The final step, 6, communicates the results in an appropriate manner. In accordance with Brundtland's definition of sustainable development, we take the temporal boundary to be at least one generation (say 20–30 years). However, setting a time horizon too far into the future increases the uncertainty, diminishing the operational usefulness of the analysis.

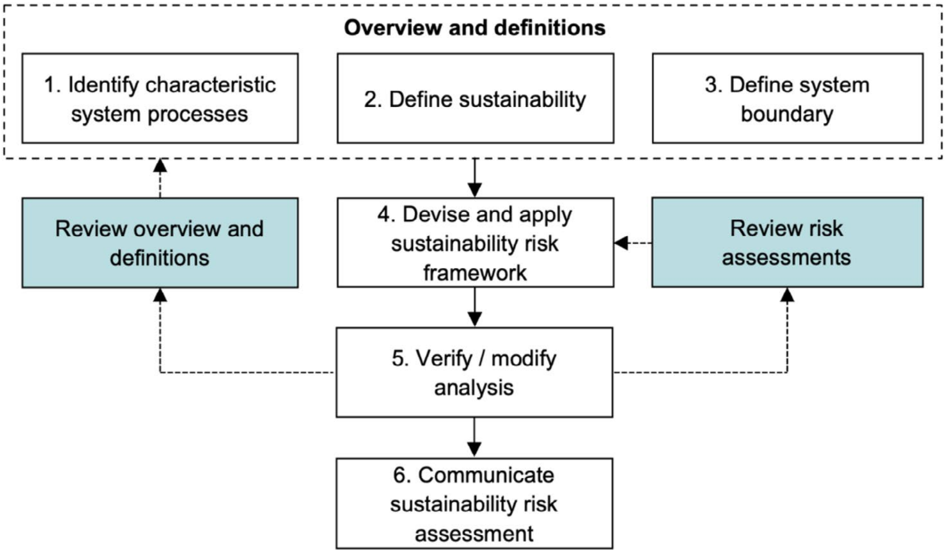


FIGURE 2 | Sustainability-risk assessment method.

In assessing the impact of a risk event on sustainability we use the triple-bottom-line accounting methodology (Dalal-Clayton and Sadler 2014). Although the theoretical underpinning of this approach is not strong (Purvis et al. 2019) our experience is that risks can be identified and sufficiently well assessed from their impact on one or more of the three stores of value (capital stocks) (Axon 2019). We use the term 'stores of value' as this implies a dynamic system which not only can be added to or depleted, but one in which the quality of the store content can be changed for better or worse. The link between stores of value and sustainability suggests the premise that the ability of future generations to meet their own needs is improved by increasing the stores of value available to them, and impaired when the stores of value are reduced. Our definitions of the three stores of value are conventional, and can be summarised:

a. Human/social capital combines the value of personal attributes such as knowledge, skills, resourcefulness, imagination, creativity, integrity, and physical strength with the added value present in societal groups organised through formal or informal institutions.

b. Economic capital is money in all forms together with the financial value of artefacts like buildings, equipment, infrastructure, and intangible assets—intellectual property and designs.

c. Environmental capital is the value found in the natural world of air, water, and land, including complex entities such as rain forests and whole landscapes, with their interdependencies and genetic diversity.

3.1 | The Sustainability-Risk Framework: Risk Discovery

Risk discovery—devising and applying a framework to identify the system processes which may cause a negative sustainability impact is central to the assessment. The negative impact is caused by a 'risk event', as shown by the causality chain in Figure 3.

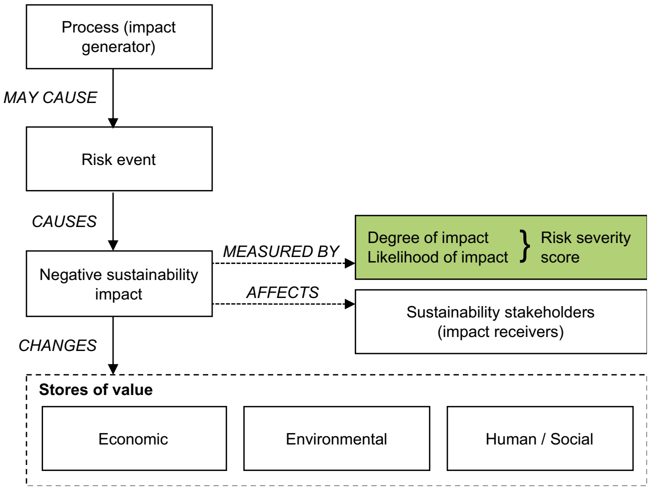


FIGURE 3 | Sustainability-risk framework.

Risks may be identified from accounts of previous performance of the system, or of similar systems. We note that although risk is sometimes articulated explicitly in reports of system operation, more often its presence is only implied through mention of barriers, bottlenecks, challenges, concerns, difficulties, issues, problems, threats, uncertainties, and the like. Analysis is then needed to identify which system processes generate the risk, and the nature of the risk event.

To assess the sustainability-risk, it is essential that *all* system processes are examined systematically, and a thorough inventory of these—the system overview—is necessary. Comprehensive risk discovery considers the entire range of risks that could lead to a negative sustainability impact above a certain threshold of severity and scale. Following experience with this type of risk discovery (Axon and Darton 2021b, 2021c, 2023, 2024) we adopt the approach of screening for risks separately for the causes of risk identified for each process with prompts tuned to the nature of the system. Risk discovery is assisted by considering the flows of capital into and out of the system, and the changes of capital (in quantity and/or quality) caused by risk events. The chain of custody of each risk, that is its generator, impact and receiver, must be evident with a pathway linking cause to effect, as suggested in Figure 3. Risks are discovered by:

1. A systematic review of literature and reports of system operation, identifying the most common issues that can be interpreted as risks.
2. Checking the causes of risk for each resource and each process to ascertain whether it is relevant or important. This is an exhaustive mechanism to ensure full coverage.

By considering all the processes that comprise the system, the location and type of risks can be established, and the overall risk to sustainability can be quantified.

3.2 | Quantifying the Risk

A risk event is assessed by its degree of impact (I) and likelihood (L), both measured on pre-determined scales. Depending on the risk severity score ($=I \times L$), a 'Risk consequence level' is assigned. Risks can only be measured with the precision appropriate to the detail and data available about system operations. The level of detail of the system description must be enough to enable all significant impacts to be captured, but not so much as to make the analysis intractable. In our work on risk in fuel supply chains (Axon and Darton 2021b, 2021c, 2024) we estimated risks using a 3×4 likelihood-impact matrix. Using a modest number of levels minimizes the possibility of risk misattribution (category error) (Axon and Darton 2021c), particularly when dealing with a mixture of quantitative and qualitative data. A large volume of published information was used to underpin estimates of risk likelihood and impact, but the scale of operations and complexity involved in such chains did not warrant any finer degree of granularity. An organization reviewing its own performance would probably have more information (e.g., statistical data) about its operations, justifying say 4×5, 5×5 or greater levels of detail. For the case study, a 3×4 matrix adequately demonstrates the method. The descriptors we use, with scores, are given in Tables 1–3.

The assessment of impact also takes into consideration the resilience of the system experiencing the risk. Greater resilience will tend to reduce impact. In the case of sustainability-risk, that resilient system is, in general terms, the one that will provide the capability to meet the needs of future generations. For each risk event a view needs to be taken on the resilience capability – the degree to which capital can be replaced, regenerated, or substituted.

TABLE 1 | Likelihood scores and indications of frequency.

Descriptor	Score	Frequency of risk event	Definition
Rare	1	Once in 10 years, or less	Only in exceptional circumstances
Possible	2	Once in 10 years	May occur
Likely	3	Once in 1 years, or more	Expected to occur

In Table 3, the suggested 'Required Response' provides a check on the consistency of the risk scores. If it seems inadequate, or excessive, either the scores should be adjusted appropriately, or special circumstances should be identified that explain the disparity.

3.3 | Scale of Risk

In the analysis we note a scale indicator of the activity which is the source of the risk. The scale categories we use are micro (local or regional, within project, site, or business-to-business), meso (national, governmental, multiple sites and actors), and macro (global, international relationships). Understanding also the scale at which different stakeholders are operating, helps explain the context of a risk event, the likely resilience, and possible risk mitigation requirements (Axon and Darton 2021c). It is helpful to understand how mitigation of a risk may come about. The difficulty of mitigation tends to increase from micro to macro, dominated by the number and complexity of international interactions. Micro- and meso-scale sources of risk can be tackled at a national level with regulation and policy.

TABLE 2 | Impact scores and their definitions.

Descriptor	Score	Definition
Insignificant	1	Impact is at edge of normal or accepted variability
Minor	2	Recoverable short-term loss
Moderate	3	Recoverable but sustained loss
Major	4	Irrecoverable loss

TABLE 3 | The consequence level and suggested response.

Consequence level	Risk score range	Required response
Low	1–2	None – these risks are within the expected range. Resilience level is satisfactory.
Moderate	3–6	Ranges from 'watching brief' to some action required (technical or policy). Some resilience is exhibited.
High	>6	Mitigation plans must be in place, or policy needs immediate attention to reduce the risk level. Little resilience is exhibited.

4 | Applying the SRAM to Liquid Biofuel Production and Use in the UK

To illustrate this method we study the production and use of liquid biofuels in the UK. This case study includes sufficient complexity, with multiple businesses involved in supply chains including the import and export of raw materials and finished goods. Liquid biofuels, mainly intended for use in transport, are claimed to be more sustainable than the fossil fuel that they replace, so understanding their sustainability performance is important (CCC 2025; RAE 2017). The sustainability-risk analysis relating to fuel supply chains is supported by an extensive literature from various sources (academic, business, government, international agencies) which provides evidence for the wide variety of risks that can occur (Axon and Darton 2024).

In 2023, bioliquids comprised around 5% of the total road transport fuels supplied in the UK (DEFRA 2024). The transport sector accounts for 97% of the UK's bioliquid fuel consumption, promoted by the requirement for producers to add bioliquid fuel to B7 diesel (up to 7% by volume, mostly Hydroprocessed Esters and Fatty Acids—HEFA). Also, the commonly sold E10 gasoline must contain up to 10% bioethanol. Of these bioliquids, 70% was imported in 2023, but importation, which leads to additional GHG emissions, is expected to decline to nearly zero by 2050, when most domestic transportation (cars, buses, trucks, watercraft, railway) should have been electrified (CCC 2025). Liquid biofuels sourced from domestic UK production could play an important role during the transition period, and possibly later for harder-to-decarbonise sectors like aviation (The Royal Society 2023) and shipping (Hsieh and Felby 2017). As imports decline, the source of this bioliquid is expected to be waste-based biodiesel and bioethanol, though HEFA will probably also be needed for blending into Sustainable Aviation Fuel (CCC 2025).

The main feedstock for UK-produced biodiesel is currently biogenic waste and used cooking oil; UK-produced bioethanol is derived from crops, mainly wheat. In 2023 the land area used for bioenergy crops in the UK (133 kha) was 2.2% of the total arable area. Of this, 48 kha was devoted to crops for bioliquids (36%), the remainder producing biomass solids and biogas (DEFRA 2024). The supply chains of bioliquids include the cultivation and harvesting of crops or the gathering of biogenic waste, transporting the feedstock to processing facilities where it is made into an acceptable liquid fuel, then distributing that fuel to consumers for use. The wide range of potential sources of biofuel, taken together with the many possible processing routes that have been developed (Cavelius et al. 2023), presents a complex picture. However, for our case study, assessing the sustainability-risks of bioliquid fuel production and use in the UK, we can assume the feedstocks and processing remain similar to the present. All biofuels used commercially in the UK are currently first or second generation, based respectively on crops, or organic wastes and lignocellulosic biomass. An assessment of the sustainability-risks of potential third or fourth generation biofuels (from biomass cultured in bioreactors), or a comparison between processing routes would require more detailed information about the options chosen, to support the analysis.

4.1 | Identifying Characteristic System Processes

System processes require energy and material resource inputs; the generic Figure 1 must be adapted for the case study. System outputs are the desired bioliquid fuel, and material and energy in forms that may be described as waste, but which may nevertheless still have value. The fuel supply chain is conceived as six consecutive stages (Axon and Darton 2024). In the first, *Exploring* for resources, the potential of different feedstocks and processing routes is measured and assessed. Exploring is a continual process which will be required as different feedstocks become available and are matched with processing facilities and the demands of the market. The second stage, *Exploiting*, comprises culture of biomass (e.g., by farming or forestry), harvesting or gathering and then transport of material to a processing site. The third stage, *Conditioning* of the feedstock, produces a liquid fuel that satisfies the specification for sale in a particular market. In general, the fourth stage is *Conversion* of the fuel into a final energy vector ready for distributing to customers, for example as electricity. However, at present in the UK virtually all bioliquid fuel is used in engines and is not converted to another energy vector, so that *Conditioning* is immediately followed by the fifth stage, *Distributing* the fuel to the final user by tanker (usually) or pipeline. In the final, sixth, stage *Using* the bioliquid fuel occurs on land or in marine or aviation applications. These stages are shown in Figure 4. Each stage (Table 4) comprises all the activities necessary for that stage including the design, setting up, operation, use and decommissioning of facilities, plant, and infrastructure.

4.2 | Working Definition of Sustainability

The sustainability of the production and use of liquid biofuel depends on the performance of the entire supply chain, from growth and harvesting or other sourcing of feedstock, through processing and distribution to the end use of the product. The working definition of sustainability reflects the important challenges in this system. For bioliquids in the UK, sourced either

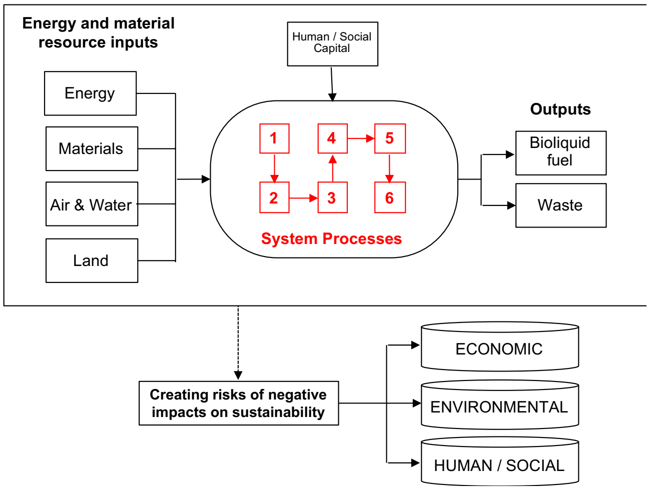


FIGURE 4 | System overview of bioliquid production and use (six process stages) in UK and their relation to the three stores of value (capital).

TABLE 4 | Process stages, and the activities characterising them, for UK bioliquid production and use. Stages three and four are combined, taking place in a (single) chemical production facility.

Stage	Characteristic activity
1. Explore	Find energy and waste crops
2. Exploit	Gather energy and waste crops
3. Condition	Chemical processing
4. Convert	
5. Distribute	Tankering
6. Use	Vehicles, stationary engines, and aircraft

by importation or domestic production (IEA 2024; Jeswani et al. 2020; Mai-Moulin et al. 2021; Welfle et al. 2023), sustainability problems include the following:

- Poor choice of land for feedstock production, or poor harvesting policy. When selecting land for cultivation of crops, or managing forest, protection of soil health and existing carbon stocks will be a consideration, as will be the preservation of ecosystems and biodiversity. There is a risk of *increasing* GHG emissions through direct and indirect land-use change. Such impacts may be difficult to identify, for example where the origin of imported feedstocks is unclear or inadequately regulated or certified.
- Bioliquid feedstock production may involve dispute about land-use rights, or unacceptable labour conditions.
- Worsening food security, through competition for farming land, or for crops, perhaps associated with rise in food prices.
- When using waste material as a feedstock, waste hierarchy principles which should govern its use may be neglected.
- Poor commercial or technical efficiency in the supply chain, which results in greater demand for resources—such as money, land, feedstock, fertiliser, water—for producing a given quantity of biofuel. Also, additional cost and energy requirements for transporting feedstocks.
- Failure to achieve targeted GHG emission reduction, perhaps associated with uncertainties in monitoring emissions and calculating counterfactual baselines used to quantify improvements.
- Failure of biofuel schemes to achieve co-benefits for people and natural systems.

Four general requirements arise from these considerations, and are included in the following working definition. Sustainable production and use of liquid biofuels requires:

i. that in the management and production of bio-feedstock negative impacts on both communities and environment are avoided or mitigated,
ii. that the supply chain's use of resources is as efficient as possible,
iii. that monitoring and certification of the whole supply chain is rigorous and transparent, and
iv. that innovations to reduce negative impacts are actively sought and rapidly introduced.

4.3 | Defining the System Boundary

This case study concerns the United Kingdom; thus the system boundary is the UK geographical national border. However, at all times the characteristics of a risk are considered at the point where it is most important or impactful which may be located outside the UK, for example in the case of imports and exports.

4.4 | Devising and Applying the Sustainability-Risk Framework

The risk generators are the processes comprising the system; the risk receivers are the relevant stakeholder(s) that is those receiving the negative impact(s). All causes of risk must have an identifiable generator and one or more receiver—a chain of custody of the risk. For this case study the risk receivers are: Communities (including NGOs and third sector organisations), Future Communities, Users, Employees, Capital providers, and Government.

To identify and measure all the significant risks to sustainability posed by the bioliquid fuel supply chain the risks can be conveniently considered in four categories. Three of these correspond to the domains of sustainability; the fourth is a cross-cutting category, termed Innovation, which comprises a group of risks that particularly affect system development, adaptability and resilience. The categories are described together with outcomes desirable for sustainability.

4.4.1 | Economic

It is desirable that the system should be part of a well-functioning market providing ready access to capital which facilitates the culture of appropriate feedstocks, the adoption of the most efficient technologies for processing these resources, and the distribution and sale of biofuel to consumers. Stable product prices, adequate profitability and a predictable commercial environment encourage such investment. Competition between markets using bio-feedstocks needs to be transparently fair and should function to avoid problems with the availability and affordability of liquid biofuel, food, and other bio-products.

Risk events could include the following (Table 5): faltering technical and commercial development due to lack of predictability, and volatility in feedstock and product price; shortages and price instability can be caused by competition for access to bio-feedstock and; poor performance of the supply chain results from inadequate investment.

4.4.2 | Environment

It is desirable that the ability of the environment to provide natural resources such as energy and minerals, land, and fresh

TABLE 5 | Economic risk: Causes and interpretation.

Cause of risk	Interpretation
Lack of a well-functioning market	Are there plenty of suppliers for feedstocks, equipment, components, systems, or services for the required activities? Is there evidence of monopolistic market actors? Is appropriate effective market regulation in place?
Lack of access to capital	Do business operations require components, systems, or services considered of an unproven nature; are investments significantly greater than normal for the size of the operation? Are commercial operations in the supply chain able to invest in (a) ongoing improvement and, (b) adherence to required performance standards?
Price volatility	How significant is volatility in the price of feedstock, processing, and product? Is there competition for resources that would give rise to market disturbance or availability issues for bioliquid fuel or food or other bio-products?

water to future generations is safeguarded, and that natural capital present in landscapes and ecosystems with biodiversity is not compromised.

Risk events could include the following (Table 6): pollution events and other technical failures and, depletion of resources increases competition diminishing future availability and impairing their quality.

4.4.3 | Human/Social

It is desirable that the bioliquid fuel supply chain benefits both individuals and communities; engagement with local communities occurs; employment with appropriate education and training is provided; operation is within the rule of law following internationally agreed best practice and ethical standards with respect to corruption, property rights, employment, fiscal matters and dispute resolution; standards and codes for products and processes are followed; negligible danger is posed to human health or safety; and public affairs are conducted with transparency and robust independent institutions are present, ensuring good corporate and governmental behaviour.

Risk events could include the following (Table 7): operation may not be acceptable to community groups; policy may not adequately consider possible social harms; farming and forestry may involve unwelcome land-use change or industrial operations; and operations may provide opportunities for corruption or other unethical behaviors.

TABLE 6 | Environmental risk: Causes and interpretation.

Cause of risk	Interpretation
Pollution event	Does the activity involve materials which would cause harmful impact if they escaped containment? How much impact on the environment would result from possible pollution events? Does the activity involve regular discharge of material damaging to the environment?
Fresh water demand	What proportion of local supply does the process require? How much impact on the environment is caused by this demand?
Lack of land availability	How would any land-use change impinge on other uses?
Depletion of material resource	To what extent does the consumption of non-renewable resource lead to lack of local availability? Does the rate of consumption of renewable resource exceed the rate of regeneration?

4.4.4 | Innovation

It is desirable for on-going technical, commercial, and societal development, including innovation of business models and structures; strong R&D capability and a good technology transfer environment in which options can be tested fairly, promising leads pursued, and dead ends terminated; and a realistic appreciation of the viability of new science and technology, and the nature of the challenges involved, including that of commercial development.

Risk events could include the following (Table 8): the inability to recognize and solve problems; flexibility and resilience are reduced; market structures and regulation may prevent new opportunities from developing or being applied in a timely manner; and optimism bias or technological lock-in diverts resources away from more effective feedstocks or technologies.

4.5 | Results

The iterative steps in the SRAM (Figure 2) for review and modification of both the overview and definitions, and of the risk assessments have been followed. These steps enable the analyst to check initial definitions against the experience of the case study to see if anomalies or omissions arise. Also, the internal consistency of numerical assessments can be verified. The definitions reported and the data shown in Figure 5 have been checked in this way.

TABLE 7 | Human/social risk: Causes and interpretation.

Cause of risk	Interpretation
Lack of public consent	Do objections from community groups remain unresolved? Is there evidence of public protest, either physical or online, even if suppressed? To what extent might activities damage artefacts or landscapes with cultural value? Are communities able to benefit from activities?
Disputed land rights or resource ownership	How serious for communities are disputes concerning land rights or ownership of resources?
Changing policy or regulatory framework	How significant is the impact on communities of operations promoted by new regulation or policy?
Corrupt and unethical practices	To what extent would activities weaken local governance (corporate or legislative) or provide opportunities for corruption and other unethical practices to flourish?
Lack of enforcement of standards and codes	Does/will activity occur in jurisdictions where regulations are unlikely to be enforced and or there is little record of improvement and engagement with international norms? This includes standards for employment, environmental impact, quality and consistency of product, and health and safety.
Human health or safety hazard	Are activities potentially hazardous for human health? Do the activities involve regular discharge of material damaging to human health? How serious might an accident be, for example caused by equipment failure, human error, or management failure.
Lack of skills in the local workforce	Is there a need to employ people from outside the locality to fill vacancies at all skill levels? Are efforts made to educate and train the local workforce?

TABLE 8 | Innovation risk: Causes and interpretation.

Cause of risk	Interpretation
Lack of improvement in commercial arrangements or regulation	Is current regulation permissive or restrictive? Are new practices or regulations being developed and deployed?
Lack of technical improvement	Is the technology mature with only incremental improvement possible? Would the R&D cease if subsidies were unavailable?
Insufficient R&D capacity or capability	Are the barriers to start R&D so high that only large organisations can afford to participate? Are there multiple actors developing new technologies, products and services, and routes to commercialisation?
Optimism bias	To what extent does optimism bias under-estimate the need for a change or over-estimate the value placed on future improvements in technologies and the likelihood of commercially success?

In the economic category the most important cause of risk is *price volatility*, arising from biofuel production competing for feedstock in food and other markets at Stage 2 and also at Stage 3 (Karkowska and Urjasz 2024). *Lack of access to capital* is a high-level risk at Stage 3 where significant capital expenditure is required for processing plants (Brown et al. 2020) and this investment is considered high risk (E4Tech 2017). Overall, economic risks score quite highly, suggesting that whilst bioliquids are often seen as a 'green' solution, they may not be the most sustainable use of economic capital. In the environment category the most important single risk is the *lack of land availability* for producing suitable biomass at Stage 2, since in the UK land is a limited resource (Booth and Wentworth 2023). This has led to the importation of liquid biofuel, potentially causing land-use change, competition with food crops and loss of ecosystem diversity elsewhere (Fehrenbach et al. 2023). *Pollution event (including GHG emissions)* remains an important cause of risk throughout this supply chain which manufactures and distributes organic chemical fuels. Impacts of spillages are partly mitigated by regulations and procedures developed from long experience with these materials, which improve resilience for example COMAH (Health and Safety Executive 2015). In the human/social category there is a wide range of risks. At Stage 2 *lack of public consent* is associated with *lack of land availability* because land-use and landscape change and farmer livelihood in this highly populated country are sensitive political issues (Rowe et al. 2022). Reports of lack of rigor and oversight of complex supply chains for imported biomass (NAO 2024) and for so-called waste imported to the biodiesel supply chain (Suzan 2025) reveal significant concern about *lack of enforcement of standards and codes* and *corrupt and unethical practices*. The 'weak verification of the origin of wastes and residues used for [biofuel production] and the potential for fraudulent activities' has been reported (RAE 2017).

In the innovation category, evidence for optimism bias at stage 2 and 6 can be found in the repeated attempts of policymakers creating short-term policy to stimulate production of biomass in the UK, and the poor experience of biomass producers, with markets failing to develop (Booth and Wentworth 2023; Ingram et al. 2025). At stages 3 and 6 there is evidence of optimism bias by funders and developers of technology which has failed to yield an acceptable combination of commercial, environmental and social performance for liquid biofuels made from biomass in the UK (Brown et al. 2020; IEA Bioenergy 2024). Concerns about *lack of technical improvement* and *insufficient R&D capacity or capability* also feature in the innovation category. This reflects the large potential scale of fuel production and the scope for cost reduction stimulating R&D internationally (Brown et al. 2020; E4Tech 2017) and the barriers to the involvement of UK industry (Vivid Economics 2019).

Stage 2—Exploit—is the stage presenting the greatest overall sustainability-risk, though Condition—Stage 3—is not far behind (Figure 5). Both stages involve novelty, in technical as well as commercial aspects. Perhaps surprisingly Stage 6—Use—also presents a significant degree of sustainability-risk, arising mainly in economic and innovation categories.

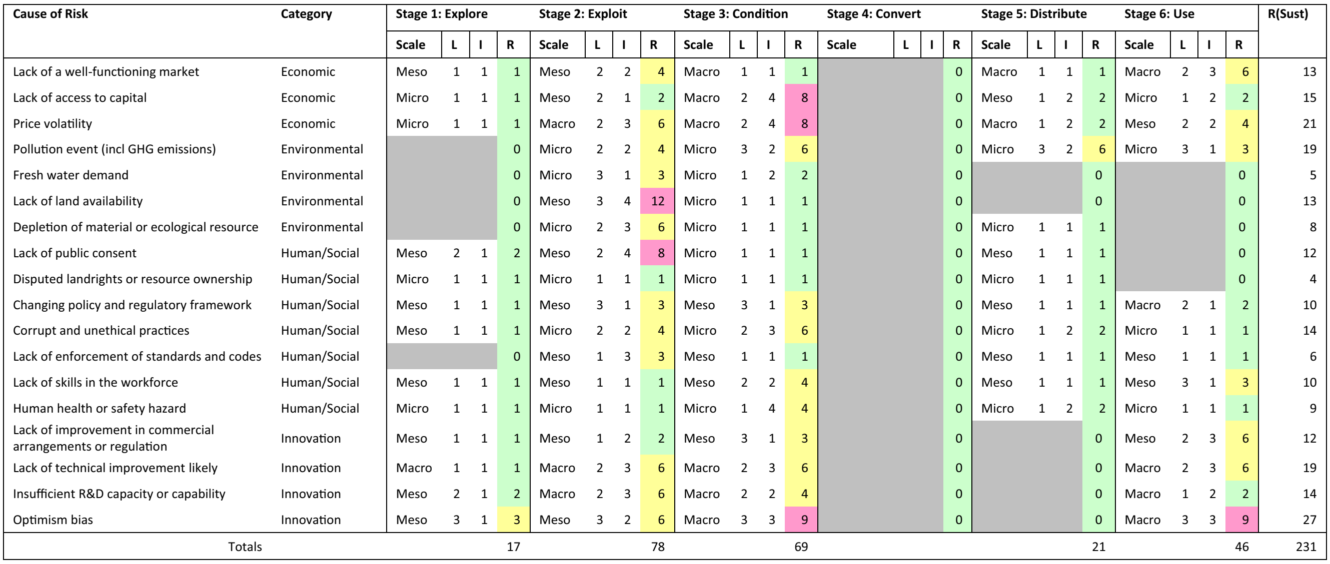
From Table 9, the highest scoring causes of risks are *Optimism bias* followed by *Price volatility*, *Pollution event*, and *Lack of technical improvement*. The method generated a wide range of sustainability-risk scores, with more than a factor of five between the highest and lowest scoring causes of risk. This range differentiates between risks and shows that all risks are appropriate for the analysis; an order of magnitude difference between the highest and lowest scores might suggest that trivial causes of risk have been included. All four categories are represented near the top of the table, but the human/social causes of risks are clustered in the lower half. Causes of risks in the environmental and innovation categories are spread throughout the table, but the three economic risks are all in the top half. Also of note is that the highest scoring causes of risk are characterized as macro-scale, while the lowest scoring are characterized as micro-scale. The causes of risk characterized as micro- and meso-scale are evenly spread.

The economic and innovation categories have a higher average sustainability-risk score (Table 10). The innovation category scores highest in both absolute and average terms. All categories are associated with at least one high-level risk. The exploitation and conditioning stages attract the most risk (Figure 5), the most technical stage (Condition) having three high-level risks (Table 11). The absolute number of risks does not vary greatly between stages, and not all incur high-level risks (Table 11).

The most important scales at which the risk occurs (Table 11) are the micro and meso. For bioliquids production in the UK, the macro-scale of international interactions—whether commercial or regulatory—is of most significance for the (technical) conditioning and use stages. We also note that the largest scale (macro) of sustainability risk occurs for three of the top four scoring risks. The meso-scale is most important for the explore and exploit stages, and the micro for the Exploit and Condition stages. For the distribution and use stage, each scale is of similar importance.

5 | Discussion of SRAM Performance

The method scores risk on a self-consistent scale, circumventing the weighting problem for negative impacts. It enables scores to be summed to give an overall measure of sustainability-risk for the system or for sub-units such as individual stages of a supply chain. This is the explicit link between sustainability expressed in a systemic framework and risk assessment, whose lack was regretted by Eckert et al. (2022). We examined the possibility of measuring benefits and disbenefits on the same risk scale, by considering as a potential sustainability-risk 'Failure to deliver [some defined] benefit for sustainability'. This stratagem fails, however. Under examination this risk is found to arise either from risks that have already been included, or from threats originating outside the system, which ought to be excluded. This confirms that trade-offs between benefits and disbenefits must be considered by a separate procedure. The need to make such a trade-off is avoided if the purpose of the analysis is to compare two or more systems producing the same product or service. We can then define this product or service as the basis of comparison, similarly to the use of a functional unit used in LCA, to see which system carries the lowest sustainability-risk to produce the same product or service.



Cause of Risk	Category	Stage 1: Explore				Stage 2: Exploit				Stage 3: Condition				Stage 4: Convert				Stage 5: Distribute				Stage 6: Use				R(Sust)
		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	2	4	Macro	1	1	1				0	Macro	1	1	1	Macro	2	3	6	13
Lack of access to capital	Economic	Micro	1	1	1	Meso	2	1	2	Macro	2	4	8				0	Meso	1	2	2	Micro	1	2	2	15
Price volatility	Economic	Micro	1	1	1	Macro	2	3	6	Macro	2	4	8				0	Macro	1	2	2	Meso	2	2	4	21
Pollution event (incl GHG emissions)	Environmental				0	Micro	2	2	4	Micro	3	2	6				0	Micro	3	2	6	Micro	3	1	3	19
Fresh water demand	Environmental				0	Micro	3	1	3	Micro	1	2	2				0				0				0	5
Lack of land availability	Environmental				0	Meso	3	4	12	Micro	1	1	1				0				0				0	13
Depletion of material or ecological resource	Environmental				0	Micro	2	3	6	Micro	1	1	1				0	Micro	1	1	1				0	8
Lack of public consent	Human/Social	Meso	2	1	2	Meso	2	4	8	Micro	1	1	1				0	Meso	1	1	1				0	12
Disputed landrights or resource ownership	Human/Social	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1				0	Micro	1	1	1				0	4
Changing policy and regulatory framework	Human/Social	Meso	1	1	1	Meso	3	1	3	Meso	3	1	3				0	Meso	1	1	1	Macro	2	1	2	10
Corrupt and unethical practices	Human/Social	Meso	1	1	1	Micro	2	2	4	Micro	2	3	6				0	Micro	1	2	2	Micro	1	1	1	14
Lack of enforcement of standards and codes	Human/Social				0	Meso	1	3	3	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1	6
Lack of skills in the workforce	Human/Social	Meso	1	1	1	Meso	1	1	1	Meso	2	2	4				0	Meso	1	1	1	Meso	3	1	3	10
Human health or safety hazard	Human/Social	Micro	1	1	1	Micro	1	1	1	Micro	1	4	4				0	Micro	1	2	2	Micro	1	1	1	9
Lack of improvement in commercial arrangements or regulation	Innovation	Meso	1	1	1	Meso	1	2	2	Meso	3	1	3				0				0	Meso	2	3	6	12
Lack of technical improvement likely	Innovation	Macro	1	1	1	Macro	2	3	6	Macro	2	3	6				0				0	Macro	2	3	6	19
Insufficient R&D capacity or capability	Innovation	Meso	2	1	2	Macro	2	3	6	Macro	2	2	4				0				0	Macro	1	2	2	14
Optimism bias	Innovation	Meso	3	1	3	Meso	3	2	6	Macro	3	3	9				0				0	Macro	3	3	9	27
Totals					17				78				69								21				46	231

FIGURE 5 | Sustainability-risk scores for bioliquids in the UK for each cause of risk and stage. Entries in grey are not relevant at that stage. Stage 4 is combined with Stage 3.

Comparing the SRAM with multi-indicator assessments we note how neglected but important features of the studied system can be assessed by the SRAM. For example, the key issue of the competition for feedstock between producers of food and producers of biofuel can readily be rated in terms of risk related to price volatility, when data would not be available to support an assessment through indicators. Similarly, risks like *optimism bias*, *lack of technical improvement*, and *corrupt and unethical practices* can be included, and their sustainability-risk assessed. Our treatment of risk, using evidence from published accounts of performance, is similar to assessments such as the Corruption Perceptions Index (Transparency International 2025) which ranks a country's public sector using surveys and expert opinion. The idea in common is to develop a consistent way of quantifying and including essential but hard-to-measure features.

Structure of the SRAM is similar to that of the PAM (Figures 1 and 2) and both were developed using triple-bottom-line accounting, but the outputs differ. The PAM measures sustainability benefits and disbenefits for system performance as they have been observed—looking back at recorded behavior to produce a set of indicators. The SRAM quantifies sustainability-risk, giving a forward look at how system processes might negatively affect sustainability. The PAM and SRAM provide distinct but complementary overviews of system performance.

The SRAM analysis of bioliquid fuel can also be compared with results from the earlier RAM study related to risk and energy security (ES) (Axon and Darton 2024). The most obvious difference is the greater number of causes of risk necessary in the ES study—34 compared to the 18 used here. The main reason for this is that many of the ES risks which cause disruption to the supply chain do not arise wholly, or to any significant extent, from operation of the liquid biofuel system itself. These risks are akin to external threats *to* the system and therefore should not be included when assessing the effect *of* the system

TABLE 9 | List of causes of risk ranked by sustainability risk score. The number for each scale is given for individual causes of risk.

Cause of risk	Category	Micro	Meso	Macro	R(Sust)
Optimism bias	Innovation	0	2	2	27
Price volatility	Economic	1	1	3	21
Pollution event (incl GHG emissions)	Environmental	4	0	0	19
Lack of technical improvement	Innovation	0	0	4	19
Lack of access to capital	Economic	2	2	1	15
Corrupt and unethical practices	Human/Social	4	1	0	14
Insufficient R&D capacity or capability	Innovation	0	1	3	14
Lack of a well-functioning market	Economic	0	2	3	13
Lack of land availability	Environmental	1	1	0	13
Lack of public consent	Human/Social	1	3	0	12
Lack of improvement in commercial arrangements or regulation	Innovation	0	4	0	12
Changing policy and regulatory framework	Human/Social	0	4	1	10
Lack of skills in the workforce	Human/Social	0	5	0	10
Human health or safety hazard	Human/Social	5	0	0	9
Depletion of material or ecological resource	Environmental	3	0	0	8
Lack of enforcement of standards and codes	Human/Social	0	4	0	6
Fresh water demand	Environmental	2	0	0	5
Disputed landrights or resource ownership	Human/Social	4	0	0	4

TABLE 10 | Sustainability-risk score by category.

Category	R(Sust) total	Number of risks	Average risk	Number of high-level risk occurrences
Economic	49	3	16.3	2
Environmental	45	4	11.3	1
Human/social	65	7	9.3	1
Innovation	72	4	18.0	2

TABLE 11 | Number of each scale of risk for each stage. Stages three and four are combined, taking place at a (single) chemical processing facility.

Stage	Micro	Meso	Macro	Risks (No.)	Number of high-level risk occurrences
1. Explore	4	8	1	13	0
2. Exploit	6	9	3	18	2
3. Condition	8	4	6	18	3
4. Convert					
5. Distribute	5	5	3	13	0
6. Use	4	5	5	14	1
Total	27	31	18		

on sustainability. Working with a smaller number of causes of risk enables the use of only four categories of risk, whereas seven were needed in the ES study. The causes of risk are identified first, and the categorization is chosen later for presentation purposes. Nevertheless, it is interesting that the innovation category turned out to be a key group of cross-cutting risks in both studies. We observe that even when the same cause of risk is considered in both analyses, it is assessed quite differently. First, the ES study considers the impact on the *dependability* of the supply chain and this is not necessarily the same as the system's impact on long-term *sustainability*. Secondly, the ES study takes into account the resilience of the supply chain itself, whereas it is the resilience of future systems for meeting societal needs that is relevant in the sustainability study.

The value of treating innovation as a distinct category is its focus on important linked risks that might otherwise be dispersed within the economic or human/social categories. The innovation risk *optimism bias* is the highest-scoring cause of sustainability-risk in the case study (Table 9). It describes the circumstance when, having chosen a particular innovation path or goal, risk events which might obstruct this are underestimated or ignored. As a result, for example, the need for consultation may be overlooked, or piloting of policy or technology skimped or omitted. The likelihood of risk event(s) is increased above what might be otherwise expected. Impacts may be greater because contingency and mitigation plans have been neglected, reducing system resilience. The motivation might be wishful thinking, lack of experience or, in a business context, reluctance to acknowledge risks that undermine the case for investment. The same bias may be widely held in a particular community, for example in a government agency, profession, sector, or company. Detecting optimism bias requires a narrative that connects the neglect of known risks to the failure of policy or technology to deliver hoped-for results. Sometimes confirmatory reports that particular risks are, or have been, neglected are available. However, individual instances of repeated failure for the same or similar reasons also suggest optimism bias. Optimism bias is a little-recognised cause of risk though with potentially serious consequences, as we found in the case study.

The common perception in much sustainability assessment is that environmental risks are the most significant, needing to be balanced against economic benefits through what is often called 'environmental sustainability assessment'. However, a comprehensive analysis shows that risks to human/social and economic capital are also common and can be important. Separating the innovation-related risks from other categories, exposes their relevance in a coherent manner. We speculate that a coordinated policy response to innovation risks might have a disproportionately positive effect on the development of liquid biofuels, and perhaps in other areas too. The need for differing policy responses emerges when interpreting the scale at which the causes of risk act. By highlighting variation between stages it becomes clear that a uniform response to the identified risks may not be appropriate or effective.

5.1 | Limitations

Essential to the discovery of risks is a pool of information relating to system performance. This information influences the overview and definitions (Figure 2) and underpins the search for and scoring of individual risks. Ideally this information should consist of unbiased and objective accounts, together with the necessary description of the context. Information may derive from a variety of sources which may be quantitative or qualitative and should enable risks to be assessed for the temporal scale chosen. As new information becomes available the risk scores can be updated—but this type of analysis is not sensitive to small changes in risk score (Axon and Darton 2021c). Detailed calculations or modelling, if available, may be included. Sometimes risk discovery is helped by reports of analogous systems incurring similar risks. An important limitation on the result of the analysis is the quality of this information—in coverage, accuracy, and bias. Sometimes there are sufficient sources to enable cross-checking. The use of evidence to identify risk is a strength, but the corresponding weakness is that in the absence of evidence a risk cannot be discovered. For some topics and system boundaries the volume of information available may be insufficient to support this type of analysis. In the method as we apply it, the focus is on risks directly linked to system operation although downstream consequences should be acknowledged in reporting. This keeps the analysis tractable but may appear to neglect the more widespread risks (partly) attributable to the system operation. For example, the environmental damage following a pollution event could cause harm to individuals and communities.

Basing risk discovery on information concerning system performance means that systemic risks will be found if reported; the SRAM is not dependent on models for predictions of such risks. Examples in the bioliquid fuel case study are *Price volatility* and

Lack of land availability which are well-known systemic risks arising from competing demands for biomass feedstock or land. Some systemic risks occurring within the system may be identified by the SRAM—for example in the case study it seems likely that *Optimism bias* is found throughout most of the supply chain. Systemic sustainability-risk can act across spatial and temporal scales (Ahlström et al. 2024) and it is important to consider these (Section 3.3); the difficulty of obtaining information about complex, and perhaps distant systemic interactions, may limit the SRAM's coverage of systemic risk.

Triple-bottom line accounting guides our search for risks spanning the widest possible range of potential impacts, notwithstanding the known disadvantages of this formalism. Gibson (2006) for example remarks that the three pillars poorly represent the common concerns of people which seldom fit neatly into these categories. Neither is it helpful that emphasizing impacts in separate domains tends to promote the idea of trade-offs between them, rather than discovering integrative solutions to problems. However, we find the approach a useful stimulus to risk discovery. In our case study, the risks discovered could be categorized with the three pillars and an additional cross-cutting category Innovation. For a different case study, an alternative categorization might be more appropriate if identified by stakeholders. All stakeholder analysis has limitations as it gives only a snapshot of that group's opinion but is useful for shaping questions or areas of greatest importance, or interest in the near future. Then using literature and information in the public domain confers transparency to the analysis.

6 | Conclusions

The SRAM characterises the sustainability performance of a process system. In the method, each sustainability-risk, which could harm the ability of future generations to meet their own needs, is linked to the activity that causes it. This identifies which processes need to be changed to improve performance. The SRAM aims to be comprehensive by discovering all relevant causes of risk with a transparency that permits adjustment as circumstances change or new information becomes available. Applying the method to a test case, the supply and use of liquid biofuel in the UK, showed that 18 causes of risk in the categories Economic, Environmental, Human/Social and Innovation were sufficient to identify the significant risks to sustainability evident from current literature reports. The SRAM method identifies and quantifies the risks to sustainability posed by the operation of the system analysed but does not consider sustainability benefits. We conclude that the SRAM can inform strategic decisions where comprehensive and systematic coverage of sustainability-risks is important.

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