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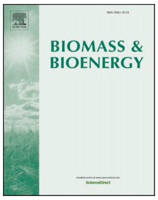

Sustainability of bioenergy – Mapping the risks & benefits to inform future bioenergy systems

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ABSTRACT

Bioenergy is widely included in energy strategies for its GHG mitigation potential. Bioenergy technologies will likely have to be deployed at scale to meet decarbonisation targets, and consequently biomass will have to be increasingly grown/mobilised. Sustainability risks associated with bioenergy may intensify with increasing deployment and where feedstocks are sourced through international trade. This research applies the Bioeconomy Sustainability Indicator Model (BSIM) to map and analyse the performance of bioenergy across 126 sustainability issues, evaluating 16 bioenergy case studies that reflect the breadth of biomass resources, technologies, energy vectors and bio-products. The research finds common trends in sustainability performance across projects that can inform bioenergy policy and decision making. Potential sustainability benefits are identified for *People* (jobs, skills, income, energy access); for *Development* (economy, energy, land utilisation); for *Natural Systems* (soil, heavy metals), and; for *Climate Change* (emissions, fuels). Also, consistent trends of sustainability risks where focus is required to ensure the viability of bioenergy projects, including for infrastructure, feedstock

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mobilisation, techno-economics and carbon stocks. Emission mitigation may be a primary objective for bioenergy, this research finds bioenergy projects can provide potential benefits far beyond emissions - there is an argument for supporting projects based on the ecosystem services and/or economic stimulation they may deliver. Also given the broad dynamics and characteristics of bioenergy projects, a rigid approach of assessing sustainability may be incompatible. Awarding 'credit' across a broader range of sustainability indicators in addition to requiring minimum performances in key areas, may be more effective at ensuring bioenergy sustainability.

1. Introduction

Bioenergy has substantial greenhouse gas (GHG) mitigation potential, provided biomass resources are sustainably sourced and efficient bioenergy systems are used [1]. As a consequence bioenergy features heavily in renewable energy and decarbonisation strategies of many countries, providing low carbon options for heat, power and transport fuels and the added potential of negative emissions provided by bioenergy with carbon capture and storage (BECCS) technologies [2]. Bioenergy can also be a catalyst in developing local and regional economic activities and the bioeconomy, such as through providing new avenues for using products, residues and wastes [3–5].

Bioenergy has a promising future, and only a small fraction of its potential has been exploited so far [6]. Bioenergy technologies will have to be deployed at scale to meet the targets of energy strategies and climate change mitigation, and consequently increasing quantities of biomass resources will have to be grown, harvested, and mobilised to balance future feedstocks demands. There are sustainability risks associated with the utilisation of bioenergy which need to be understood and managed. These risks may be intensified with increasing deployment trajectories and as countries balance their feedstock demands through the international trade markets. Trends towards longer, more complex international supply chains can already be observed [7] and sustainability challenges will likely increase with the growing distances between both the resources and supply chains, and the feedstock purchasers and bioenergy plants [8].

Bioenergy has the potential of generating both sustainability risks and benefits, that where possible should be mitigated and maximised respectively [9]. These potential impacts should be evaluated over the short-, medium-, and long-term taking account of all economic sectors, for the whole of society, for natural systems and for climate change. The sustainability risks and benefits of a given bioenergy project will reflect the activities of that project. Much the same with life cycle assessment analyses, the sustainability of bioenergy schemes will be influenced by the characteristics and boundaries of activities and processes included within the scheme and the nature of the applied approach to test its sustainability.

Achieving long term bioenergy targets sustainably will only be possible through the support of institutional and regulatory frameworks that incentivise sustainable products, practices and services; create a fair market; allow just access to resources, products and services; and prevent, if not prohibit, negative impacts [10]. Many bioenergy sustainability schemes have been developed that focus on broad and/or narrow feedstocks/technologies systems and for different geographies [11]. This includes regulatory sustainability criteria that require adherence to minimum performances for key sustainability issues [12], such as those of the European Union's (EU) Renewable Energy Directive (RED) [13]. Also a growing number of voluntary schemes that may be applied to assess and benchmark performance [14], such as Roundtable on Sustainable Palm Oil (RSPO) [15] and the Roundtable on Responsible Soy Association (RTRS) [16]. The details, merits and shortcomings of different sustainability assessment schemes are covered widely across literature [9,10,17], although a vital thread running through each scheme albeit applied differently is the definition of 'sustainable bioenergy' and how to determine whether a given project is sustainable or not.

'Sustainability' is a term that may be used to describe broad ranging themes from those impacting people and society to technology performances and economics, through to the many issues of environmental systems. 'Bioenergy' is itself also an extremely broad term that may be used to describe solids, liquids, or gases used for electricity, heat or transport fuels generated from a wide range of biogenic materials. As a consequence 'sustainable bioenergy' is far from a homogenous concept – a potential problem when developing plans, targets and regulations to ensure it is achieved. This is evidenced through the case study of the European Union when developing the sustainability criteria of the EU's Renewable Energy Directive (RED) [13], flexibility still had to be given when translating the criteria into national legislation due to the broad differences in the characteristics of 'biomass' and 'bioenergy' within each Member State [11]. This presents a challenge for the consistency of sustainability compliance and highlights the potential need for a flexible approach when assessing sustainability that reflects the many dynamics and broad ranging characteristics of bioenergy projects.

As the contribution from bioenergy increases, focus on sustainability will increase accordingly. It is vital that the full sustainability implications of bioenergy are understood to aid the development of informed support schemes, policies and regulations. Mapping the sustainability of bioenergy projects is a valuable process that enables the analysis of: the varying characteristics of projects and the different sustainability issues that are relevant; identification of the leading areas of potential risk; the leading benefits potentially gained, and; identification of sustainability trends across bioenergy projects to ensure that policies and regulations are developed that cover the consistent themes relevant to bioenergy projects [9].

This paper applies the 'Bioeconomy Sustainability Indicator Model' (BSIM) to map and analyse the sustainability of a series of UK bioenergy case studies. The aim of the paper is to evaluate the sustainability performance of each bioenergy case study. The objective is to identify trends across different biomass resources, bioenergy technologies, end uses and vectors, to provide lessons for bioenergy decision makers for improving the sustainability of bioenergy projects. The paper demonstrates how the parameters of 'bioenergy sustainability' performance will vary depending on the boundaries and characteristics of given case studies. Despite the potential contrasts between bioenergy projects, the research also identifies common sustainability trends - allowing recommendations to be drawn of the potential actions that could be pursued to ensure the leading sustainability benefits of bioenergy may be maximised, and where research, development, and policy should be targeted to ensure the leading sustainability risks are mitigated to increase the viability of large-scale bioenergy deployment.

2. Methodology – mapping the sustainability of bioenergy case studies

2.1. Bioeconomy Sustainability Indicator Model (BSIM)

The BSIM is applied to analyse the sustainability of a series of UK bioenergy case studies. The BSIM has been designed to provide a flexible tool to map the sustainability of different biomass resources, supply chains, technologies, and/or whole bioenergy value chains. The flexibility of the BSIM and range of sustainability issues that it can potentially map, makes it a state-of-the-art tool well suited for the analyses targeted in this research.

The BSIM is an open access tool that can be found online [18] and is supported by the BSIM Guidance Manual [19] and previous research that demonstrates its application [9]. Fig. 1 provides a schematic of the overall approach of the BSIM.

(1) The BSIM is developed based on the principle that there may be both sustainability risks and benefits attributed to each life cycle step within any bioenergy or bioeconomy project, and these sustainability risks and benefits can be mapped. (2) A comprehensive list of sustainability issues was identified covering each life cycle stage of potential bioenergy or bioeconomy projects. (3) These issues are structured within a sustainability assessment framework following a hierarchy: broad Sustainability Categories (e.g. natural systems), Sustainability Themes (e.g. land), Sustainability Indicators (e.g. soil) and individual Sustainability Issues (e.g. soil organic carbon). The BSIM is calibrated by first identifying sustainability issues that are relevant to a project and then by assessing the potential occurrence of sustainability risks or benefits by applying scores. Each sustainability issue also has a weighting value to account for greater or lesser potential influence compared to all other issues considered. (4) The BSIM generates outputs mapping the key sustainability risks and benefits and calculates sustainability scores for the project based on the individual indicator scores and weightings. Sustainability scores for a given project are index values that allow comparison between projects. (5) The BSIM also maps the potential influence a bioenergy and bioeconomy project may have on the United Nation's Sustainable Development Goals (SDGs). Further description of the BSIM's method and calculation mechanics are presented in the BSIM Guidance Manual [19].

2.2. *BSIM's sustainability assessment framework*

The BSIM's sustainability assessment framework includes coverage of 126 different sustainability issues. These are structured within 4 Sustainability Categories, 16 Sustainability Themes and 38 Sustainability Indicators. Table 1 provides a summary of the categories, themes and indicators covered by the BSIM. A full list of all 126 sustainability issues is included within the Supplementary Materials and descriptions of each are included in the BSIM's Guidance Manual [19].

Table 1
Sustainability indicator assessment framework.

Sustainability Indicator Framework		
Categories	Themes	Indicators
People	Health	*Health & Wellbeing*
		Food Systems
		Land Management
	Livelihoods	*Decent Work*
		Jobs & Skills
		Change in income
	Society	*Equality*
		Peace, Justice & Strong Institutions
		Partnerships
		Energy Access
Development	Economy	*Economic Performance*
		Economic Stimulation
	Infrastructure	*Infrastructure Requirements*
	Feedstocks	*Production Processes*
		Mobilisation
		Distribution
	Technology	*Innovation*
		Efficiencies
		Techno-Economics
	Energy Sector	*Bioenergy*
		Energy System Performances
	Bioeconomy	*Added Value Products*
		Bioenergy Complementing Wider Sectors
	Land Utilisation	*Land Utilisation*
Natural Systems	Land	*Soil*
		Ecosystems
	Air	*PM Pollutants*
		Oxide Pollutants
		Heavy Metal
	Water	*Water Use & Efficiency*
		Water Quality
		Water Systems
Climate Change & Emissions	Governance	*Climate Action*
		Standards
	Carbon & Emissions	*Whole Life Cycle Emissions*
		Land & Carbon Stocks
		Counterfactual Considerations
	Energy System	*Replaced Fuels*

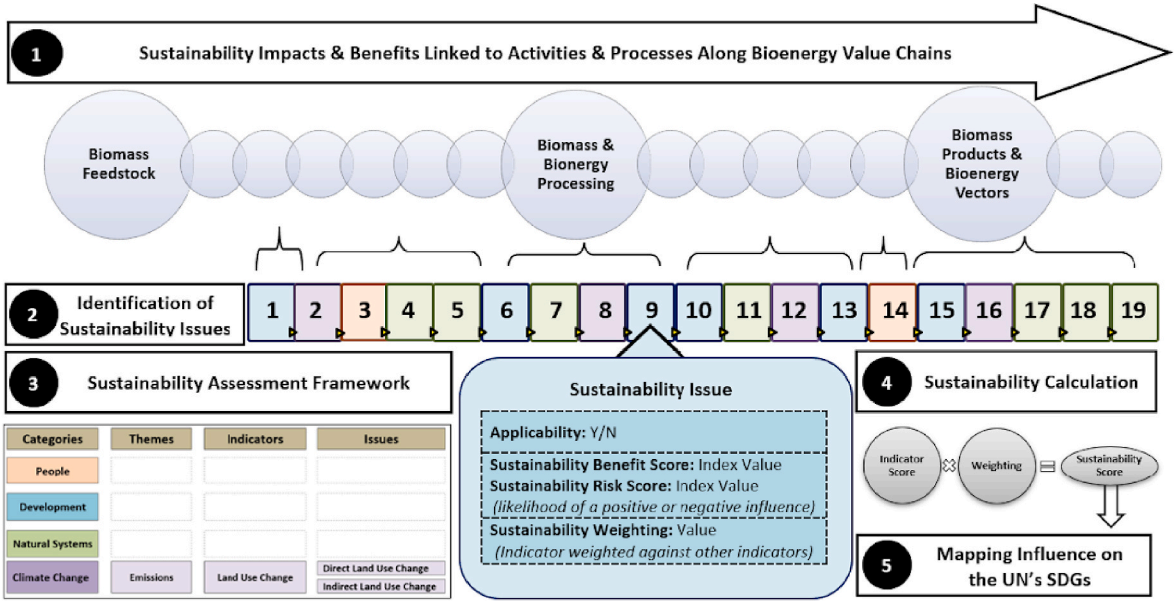

Fig. 1. Bioenergy sustainability indicator model architecture.

2.3. Applying the BSIM to map the sustainability of bioenergy case studies

2.3.1. Bioenergy expert engagement

To assess the sustainability of UK bioenergy case studies, this research engaged with bioenergy experts that provided representation of a range of current bioenergy research projects in the UK. Engagement focused on the bioenergy researchers who have completed projects funded by the UK Supergen Bioenergy Hub [20], covering a broad range of biomass feedstocks, conversion and pre-treatment technologies, end uses and vectors. This allowed inclusion of expertise from across the many disciplines of bioenergy and from leading UK bioenergy research groups.

A series workshops were facilitated to discuss each researcher's projects and to introduce and explain how to use the BSIM. Researchers were given a time period to either individually or as part of their research group, apply the BSIM to map the sustainability of their projects. Sessions were facilitated to discuss the results, to ensure consistency in how the BSIM was used and to validate outputs through comparing assumptions made by different researchers/research groups.

The organisations that contributed sustainability assessments are reflected in the paper's author list and are presented in the Supplementary Materials.

2.3.2. UK bioenergy case studies

The sustainability of 16 UK bioenergy case studies are mapped and analysed. The case studies are used to identify both unique findings and common sustainability trends across different types of bioenergy projects. Fig. 2 provides a summary of the case studies that are loosely grouped within 4 categories, case studies focusing on: production and mobilisation of bioenergy feedstocks (green – Case Studies 1–3); processing and conversion of feedstocks into bio-products (yellow – Case Studies 4–7); bioenergy products or vectors (blue – Case Study 8), and; full bioenergy value chains (purple – Case Studies 9–16). The black boundaries highlight the feedstocks, technologies and activities included within each case study. The coloured shading and boundaries document the focus and limits of the sustainability mapping analyses using the BSIM.

Fig. 2 demonstrates both the varying characteristics and system boundaries across the case studies, and variations in the focus of the sustainability assessment applied to each. For example, CS4 is developed to reflect a research project where biomass substrate/wastewater is used as a feedstock, catalytic processes are applied, the products are converted within a gasifier to produce a hydrogen/biomethane rich syngas and there is potential for CCS. The sustainability mapping for CS4 focuses on the pre-treatment and conversion of the feedstock elements of the wider value chain.

2.3.3. Summary of the UK bioenergy case studies

Summaries of the case studies are provided below. Further details and the full BSIM calibration settings for each case study are included within the Supplementary Materials.

CS1 - Imported Energy Crops: Assessment of the global implications of importing biomass feedstocks to meet UK demand. Focusing on energy crops, CS1 focuses on the production, mobilisation and transport of feedstocks for UK end markets.

CS2 - Miscanthus on Marginal Land: Assessment of the potential production of miscanthus on lands that currently have limited agricultural value. CS2 focuses on the production of miscanthus on UK marginal land identified using the MiscanFOR model [21], and the transportation of the resource to central processing sites [22].

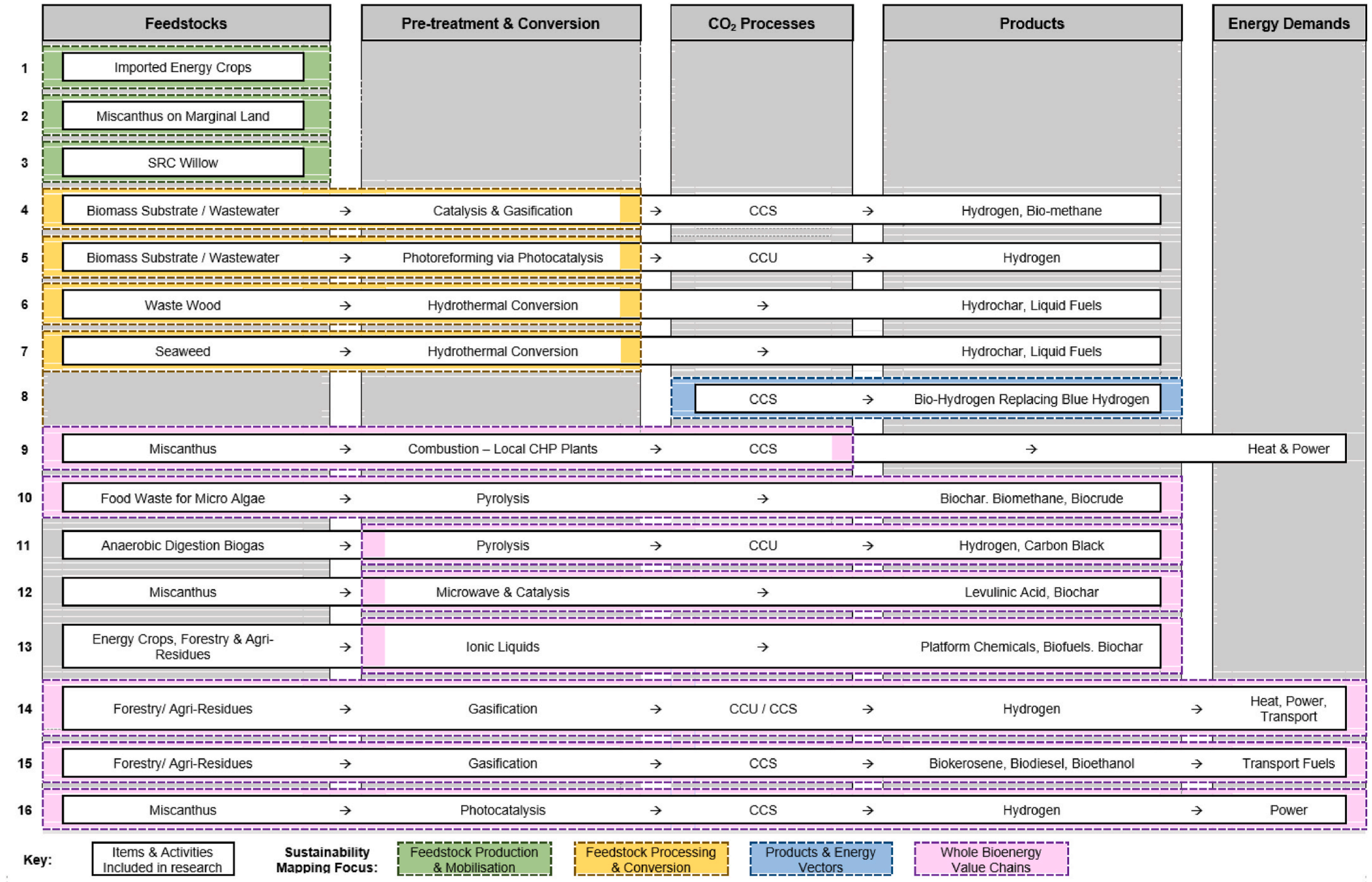

Fig. 2. UK Bioenergy Case studies & the Focus of Sustainability Mapping Analyses.

CS3 – Willow SRC on Agricultural Land: Assessment of willow short rotation coppice (SRC) grown on UK farmland. The sustainability assessment focuses on issues related to land use and the production and cultivation of willow. CS3 assumes that willow is planted on previously either arable or rotational grassland on a nonorganic soil (not drained lowland peat).

CS4 – Hydrogen from Biomass Wastewater via Catalysis & Gasification: System where hydrogen and biomethane are generated from industrial biomass wastewaters high in chemical oxygen demand (COD) and total organic carbon (TOC), such as olive processing water, stillage and spent lees. The feedstocks are processed through a continuous hydrothermal process at a low gasification temperature (430 °C) and short residence time (20 s), by combining supercritical water gasification (SCWG) and partial oxidation with in-situ formation of new metal oxide nanocatalyst (e.g. iron oxide). This results in continuous generation of a syngas rich in hydrogen and biomethane, a water product low in COD and TOC, and the generation of metal oxide nanocatalyst as the secondary product [23]. CS4 focuses on assessing the sustainability of the pre-treatment and conversion of the feedstocks.

CS5 – Hydrogen from Biomass Wastewater via Photocatalysis: Hydrogen is generated from biomass substrate or wastewater through application of small-scale photocatalytic converters. The biomass feedstocks are chemically converted through irradiation from natural (e.g. solar) and renewable energy powered artificial sources (e.g. LEDs linked to photovoltaic systems). Hydrogen is produced through the photoreforming of the organics [24]. CS5 focuses on assessing the sustainability of the photocatalysis technologies and conversion of the feedstock.

CS6 – Hydrochar & Liquefied Value-Added Products through Hydrothermal Conversion of Wood Residues: Sawdust residue is converted through a semi-continuous flow hydrothermal system, resulting in liquid products and hydrochars (solid residue) that were investigated for potential energy and water treatment applications [25]. CS6 focuses on assessing the sustainability of the hydrothermal conversion of the wood feedstock.

CS7 – Hydrochar & Liquefied Value-Added Products through Hydrothermal Conversion of Seaweed: Brown seaweed (Laminaria digitata) is converted through a semi-continuous flow hydrothermal system, resulting in liquid products and hydrochars (solid residue) that were investigated for potential energy and water treatment applications [26]. CS7 focuses on assessing the sustainability of the hydrothermal conversion of the seaweed feedstock.

CS8 – Biohydrogen replacing Blue Hydrogen: Assessment of the relative sustainability risks and benefits of using biomass-hydrogen to displace blue hydrogen production (natural gas reforming with CCS) [27,28]. CS8 assesses the additional impacts (and avoided impacts) that would result from replacing blue hydrogen including on the supply chain for natural gas (including fugitive emissions).

CS9 – Miscanthus as a Feedstock for Local CHP with CCS: Miscanthus is produced as a feedstock for local power stations with linked CCS infrastructure. CS9 assumes that miscanthus is produced using perennial rhizomes over a 20-year timeframe, herbicide and fertilizer is only used at the beginning of the life cycle with limited field management between early spring harvests [29]. Harvested resource is transported to local small to medium scale combined heat and power (CHP) plants where up to 90% of biogenic carbon is captured through post combustion CCS technologies and infrastructure [30]. The CS11 sustainability analysis focuses on the production of miscanthus and the conversion and carbon capture technologies.

CS10 – Biofuels & Bioproducts from the Pyrolysis of Microalgae Cultivated on Food Wastes: Microalgae are grown within a novel photobioreactor on a supply of nutrients from food processing wastes. The algae are isolated through a film-scraping step to be feedstocks for pyrolysis thermal conversion. The system generates a range of products including biomethane, biocrude and biochar. Sustainability analysis focuses on the complete bioenergy value chain.

CS11 – Hydrogen from the Pyrolysis of Biogas: Hydrogen is produced through pyrolysis of biogas generated through an anaerobic digestion process. Biogas is converted through fast pyrolysis to generate a hydrogen rich syngas and solid carbon material (carbon black) [31]. The sustainability analysis for CS11 focuses on the conversion technologies and onward use of hydrogen as a fuel.

CS12 – Platform Chemicals through Conversion of Miscanthus using Microwave Catalysis: Levulinic acid (a precursor to biofuels) is produced through the catalytic conversion of miscanthus feedstock. Miscanthus is converted using a novel microwave, mild heating and catalysis (sulphated zirconia with dilute HCl) processes to hydrolyse the cellulose, producing levulinic acid and high density biochar material [32]. The CS12 sustainability assessment focuses on the processing and conversion technologies and the resulting products.

CS13 – Platform Chemicals & Biofuels through Ionic Liquid pretreatment of Lignocellulosic Biomass: Lignocellulosic materials such as energy crops, forestry and agri-residues are processed using the ionoSolv pre-treatment fractionation process. Protic ionic liquids are applied to break down the cellulose, lignin and hemicellulose fractions of the biomass to allow separated valorisation [33]. The cellulose fraction is used to produce platform chemicals, biofuels and cellulose-based materials; lignin is used for energy and materials; hemicellulose is used for the production of platform chemicals such as 5-(hydroxymethyl) furfural (HMF) and furfural. CS13 focuses on analysing the sustainability of the catalytic conversion processes and the resulting products.

CS14 – Gasification of Forestry/Agri-Residues to fuel Hydrogen Fuel Cells: Forestry and agri-residues are converted through a gasification conversion process to generate hydrogen for fuel cell technologies. Focusing on sawmill residues that are dried and pelletised to provide a uniform feedstock for an entrained flow gasifier, to generate a hydrogen rich syngas. CO_2 is captured for long term storage or utilisation within industry [34]. CS14's sustainability assessment covers each step within the case study life cycle including the onward energy applications for hydrogen.

CS15 – Gasification of Forestry Residues to Produce Sustainable Aviation Fuels: Forestry residues provide a feedstock for gasification to produce a syngas allowing generation of a range of fuels and products. Oxygen is used as a gasification agent within high temperature and pressure conditions in the presence of a dolomite catalyst, and the resulting syngas is cleaned (tar removed) and conditioned using a water gas shift (WGS) unit to allow conversion through a Fischer Tropsch process to produce biocrude. The Fischer Tropsch process is applied to convert and upgrade the biocrude through hydrotreatment, green hydrogen is used to perform hydrocracking and isomerisation. CO_2 generated by the WGS is removed through a carbon capture unit enabled by a Selexol solvent. The upgraded biocrude is separated generating a series of fractions, i.e light gasses, sustainable aviation fuel (SAF), gasoline, diesel and waxes [35]. CS15's sustainability assessment covers each step within the case study life cycle including the onward applications of the products.

CS16 – Hydrogen from Miscanthus via Photocatalysis: Hydrogen is generated from miscanthus through application of small-scale photocatalytic converters deployed locally to allow on-site energy generation for the agricultural sector or nearby communities. Miscanthus is chemically converted through irradiation from natural (e.g. solar) and renewable energy powered artificial sources (e.g. LEDs linked to photovoltaic systems). The hydrogen is produced through the photoreforming of the organics [23]. CS16 assumes an advancement in photocatalytic technology (e.g. TRL 7–9) which would facilitate large scale deployments. The sustainability assessment covers each step within the case study life cycle including the onward applications of the products.

3. Results

3.1. Bioenergy case study sustainability maps

The radar graphs (Fig. 3) map Sustainability Performance Score (SPS) values from the BSIM at the sustainability Indicator resolution for each of the case studies. SPS are index values that are calculated as a function of the scores allocated for each issue to reflect the potential for sustainability risks and/or benefit (IS - Issue Scores) and the respective weightings of each sustainability issue within the BSIM (IW - Issue Weighting). Full IS and IW scores for each case study are presented in the Supplementary Materials and further descriptions of the BSIM's units and calculation mechanics are discussed in depth externally [9,19].

As demonstrated by the key in Fig. 3, the radar graphs are shaded to delineate the different sustainability categories of the BSIM. The 'yellow' segments for the People sustainability indicators, 'blue' for the Development indicators, 'green' for Natural Systems and 'orange' for Climate Change & Emissions. Where indicators are shaded 'grey', they have not been selected by the bioenergy researchers to analyse their case study - typically because they are not considered relevant, or within the case study's boundaries. The shading of each radar graph allows a clear visual assessment of variations in the extent that different sustainability indicators are deemed to be relevant to the different case studies. The 38 spokes of the radar graphs each represent a different sustainability Indicator, the green and red lines highlight the potential sustainability benefit and risk SPS values calculated for each. For example, the CS2 radar graph demonstrates that this case study may result in potentially high sustainability risk for *Water Use & Efficiency* (Indicator 30),

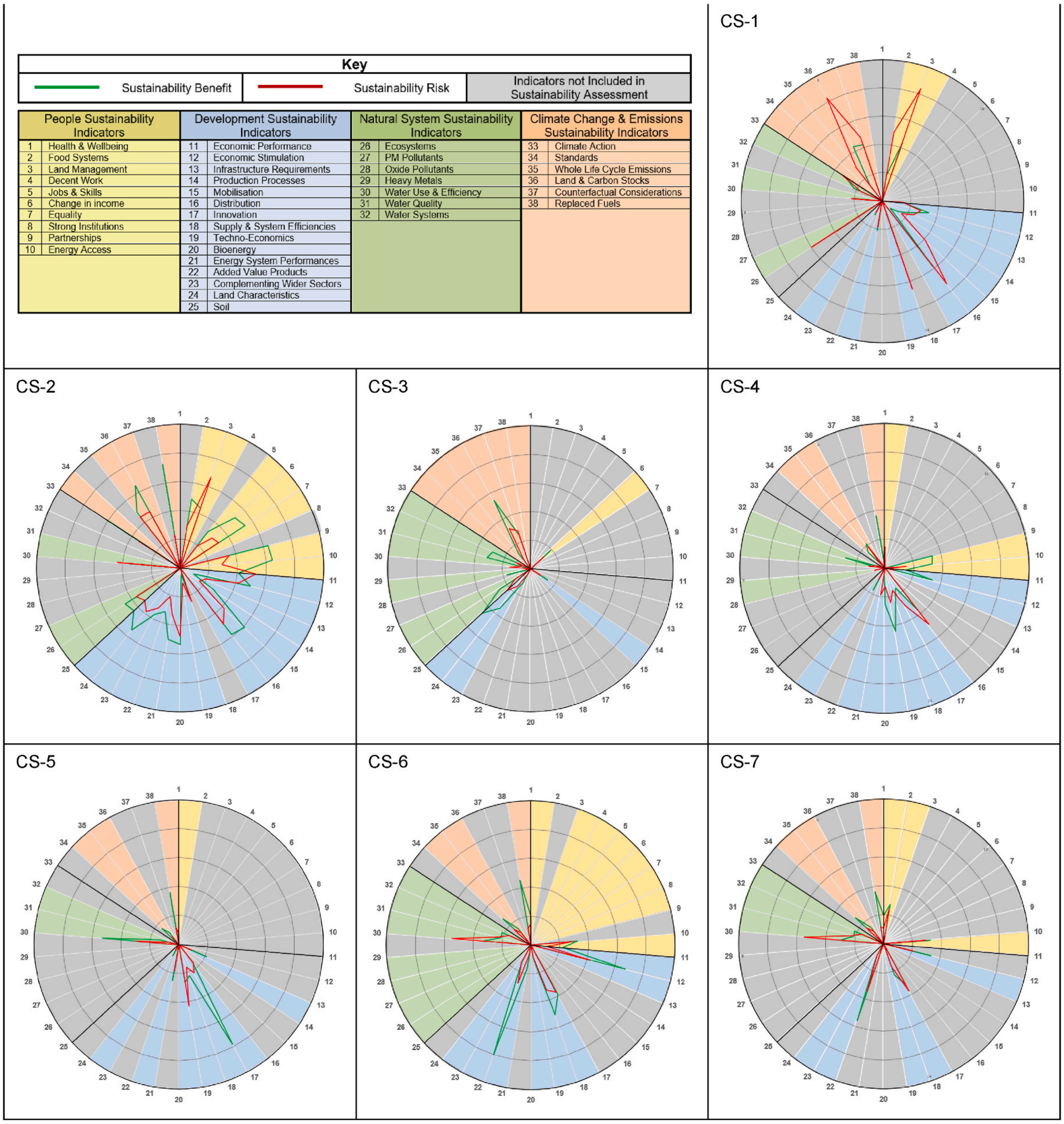

Fig. 3. Radar Graphs for each Bioenergy Case Study, Mapping the Risks & Benefits across the 38 Bioenergy Sustainability Indicators of the BSIM. Each figure presents the Sustainability Performance Score (SPS) values from the BSIM at the sustainability Indicator resolution. Radar graphs are shaded to delineate the different sustainability Categories of the BSIM: 'yellow' segments for People sustainability Indicators; 'blue' for Development Indicators; 'green' for Natural Systems and 'orange' for Climate Change & Emissions. 'Grey' segments of the graphs reflect Indicators not assessed within each Case Study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

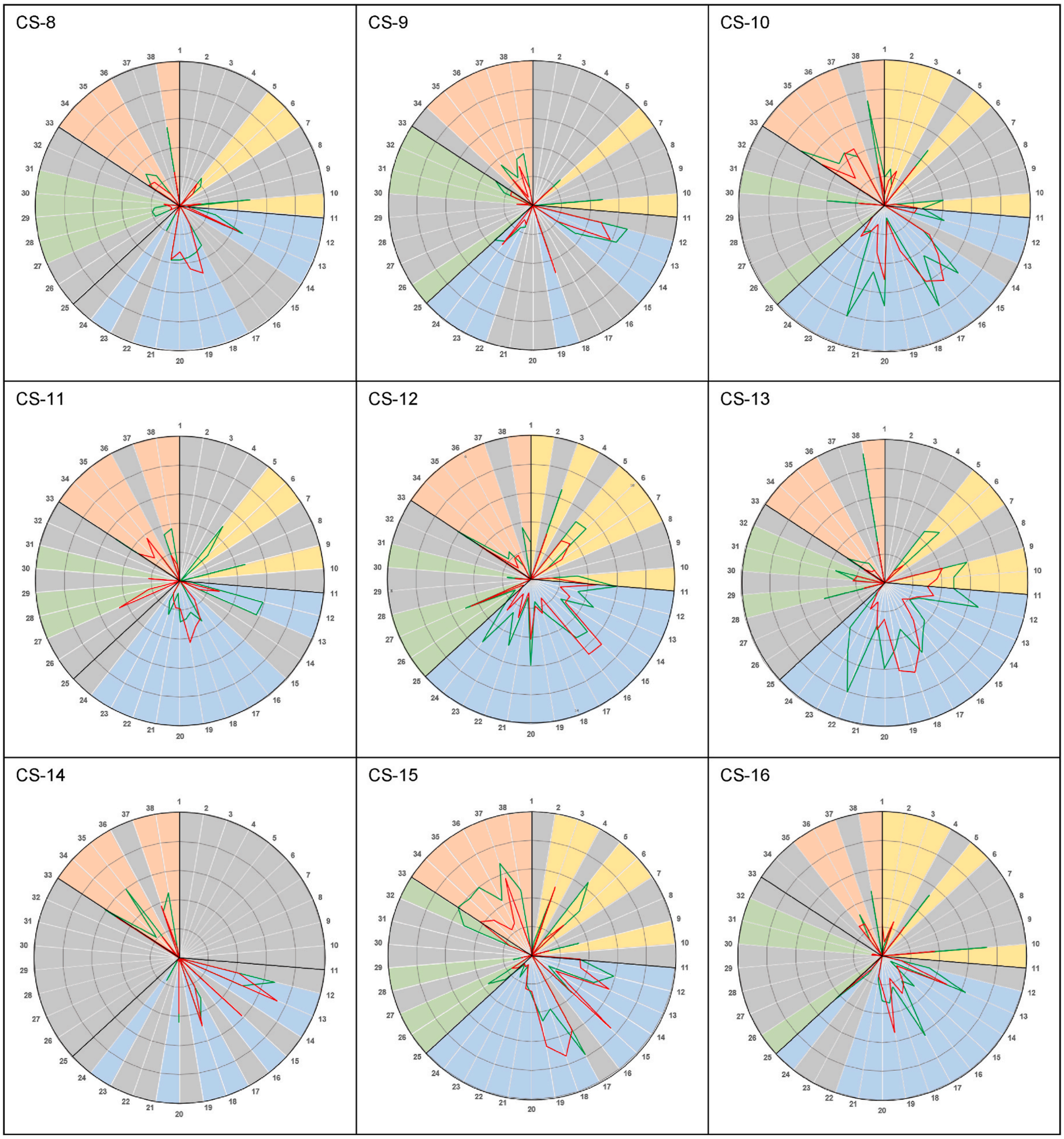

Fig. 3. (*continued*).

potential high sustainability benefit for *Replaced Fuels* (Indicator 38) and there is potential for both risk and benefits for *Economic Performance* (Indicator 11).

The SPS data presented in Table 2 complements Fig. 3's radar graphs, in highlighting the overall balance of sustainability performances. These provide an assessment of whether a given case study may provide risks or benefits for each Sustainability Indicator, Theme or Category. For example, the SPS data for CS1 clearly highlights this case study has the potential to generate greater sustainability risk than benefits across each of the sustainability categories (People, Development, Natural Systems, Climate Change). In contrast CS2 is shown to have the potential to generate greater benefits than risks across each Category. It is important to use both Fig. 3 and Table 2 when interpreting the results as there are occurrences where close parity is calculated in the SPS for both the sustainability risk and benefit - as a consequence the balance results within Table 2 will not adequately reflect high sustainability potentials. Full presentation of the BSIM output results from each case study are included within the Supplementary Materials.

Fig. 4 is designed to allow analyses of the SPS scores at the different resolutions of the BSIM's sustainability assessment framework. For each sustainability Category, Theme and Indicator the extent of the high and low error bar demonstrates the minimum and maximum SPS values across the 16 case studies, the range of the shaded bars highlight the 1st and 3rd quartile SPS values. The red and green shading highlights the extent that sustainability risk and/or benefit is calculated across the case studies. For example, focusing on Development at the Category resolution, the error bars demonstrate that there are both case studies where an overall sustainability risk is calculated and case studies where an overall sustainability benefit is calculated; whilst the dominance of the red shading of the bars demonstrate that across the case studies there is a greater balance towards there being a sustainability risk rather than a benefit.

Analysing the SPS at the different resolutions allows assessment of how the overall sustainability performances are calculated. Again, focusing on the Development Category, the SPS values at the Theme and Indicator resolutions highlight that balance towards sustainability risk is

Table 2

Balance of Sustainability Performance Scores for each Bioenergy Case Study. Indicating the balance of risks and benefits calculated across the BSIM's 38 sustainability indicators.

Category	Themes	Indicators	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	CS-9	CS-10	CS-11	CS-12	CS-13	CS-14	CS-15	CS-16
People	Health	Health & Wellbeing	-	-	-	-1.83	-0.74	0.61	1.06	-	-	1.52	-	2.33	-	-	-	-2.21
		Food Systems	-3.83	2.36	-	-	-	-	0.39	-	-	1.02	-	-	-	-	0.55	-0.21
	Livelihoods	Land Management	-4.95	-2.87	-	-	-	-	-	-	-	-1.30	-	4.05	-	-	-0.17	-0.42
		Decent Work	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Jobs & Skills	-	1.61	-	-	-	-	-	0.61	-	1.76	6.01	2.09	3.77	-	6.20	3.26
		Change in income	-	2.67	0.91	-	-	-	-	0.91	0.95	-	3.24	1.91	3.71	-	2.00	-
	Society	Equality	-	2.76	-	-	-	-	-	-	-	-	-	-1.51	-	-	-	-
		Strong Institutions	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Partnerships	-	3.49	-	4.21	-	-	-	-	-	-	5.78	-	1.16	-	1.78	-
		Energy Access	-	4.41	-	2.20	-	0.37	0.37	4.22	6.06	4.13	-	2.20	0.96	-	-	4.12
Development	Economy	Economic Performance	-0.03	-1.49	-	1.39	-	1.37	-	-0.01	-	0.42	0.93	1.78	1.79	-	0.11	-
		Economic Stimulation	0.71	1.06	-	3.33	-	3.16	1.58	2.28	0.10	2.63	3.86	1.58	3.22	3.16	3.11	1.74
	Infrastructure	Infrastructure	-0.44	-1.13	-	-	0.90	-	-	0.40	-0.69	-	5.37	2.23	-0.01	-3.27	-0.84	1.28
	Feedstocks	Production Processes	-0.29	1.47	0.73	-	-	-	-	-	2.93	-0.66	-	-0.51	-0.05	-	-0.40	-0.42
		Mobilisation	-4.24	2.42	-	-	-	-	-	-	-	2.34	-	-1.64	2.27	-4.41	-3.54	1.40
		Distribution	-1.91	1.16	-	-1.58	-0.28	-	-	-	-	-2.72	-2.05	-1.80	1.00	-	-	-0.42
	Technology	Innovation	-	-	-	-1.73	7.00	0.28	-0.70	2.07	-	2.41	0.23	2.07	-0.12	1.15	2.83	3.82
		Efficiencies	-3.96	-0.25	-	0.78	0.81	2.26	0.78	-1.91	-1.91	-1.98	-1.27	-0.25	-3.93	-0.49	-3.19	0.81
		Techno-Economics	-	-0.79	-	2.49	-1.90	0.10	-	-0.99	-	-0.24	-2.06	-0.42	-2.14	-	-1.43	-2.55
	Energy Sector	Bioenergy	-	0.70	-	1.54	-	-	-	0.73	-	2.26	1.14	2.28	3.59	0.72	0.38	0.70
		Energy System	0.28	2.20	-	-1.82	0.67	1.22	-	0.04	-	1.68	-1.29	0.40	-0.39	-	-0.04	0.30
	Bioeconomy	Added Value Products	-	1.41	-	-	-	6.55	2.68	-	0.27	8.28	1.27	2.54	7.25	-	0.09	-
		Wider Sectors	0.22	0.65	0.79	1.04	0.31	-0.07	0.22	1.59	0.75	-0.11	0.77	1.84	3.44	1.89	0.72	-
	Land	Land Characteristics	-	2.03	2.46	-	-	-	-	-	-1.60	-0.43	-	3.46	2.71	-	0.02	0.29
Natural Systems	Land	Soil	-	1.33	2.97	-	-	-	-	-	4.95	0.18	-	1.98	-	-	1.02	0.33
		Ecosystems	-2.56	1.15	1.60	-	-	-	-	-	-	-	-	0.80	-	-	2.33	-
	Air	PM Pollutants	-	-	-	-	-	-	-	1.38	-	-	-5.70	0.51	-	-	-	-
		Oxide Pollutants	-	-	1.70	-0.92	-	-	-	1.74	-	-	-2.75	-	2.77	-	0.46	-
		Heavy Metals	-	-	-	-	-	-	-	1.35	-	-	-	-	-	-	-	-
	Water	Water Use & Efficiency	-0.25	-0.92	-1.83	-0.54	2.79	-2.71	-3.12	-0.54	0.49	2.68	-2.74	0.70	-0.19	-	-	-0.62
		Water Quality	-	-	3.14	2.70	0.60	-0.24	-0.24	-	-0.41	-	-	-	1.30	-	-	-0.59
		Water Systems	0.68	-	2.28	-	-	0.68	0.68	-	0.68	-	-	-	-	-	4.21	-
Climate Change	Governance	Climate Action	-0.46	3.36	-	-	-	-	-	-0.34	1.68	2.17	2.40	2.29	1.05	1.22	2.69	-
		Standards	-	-	-	1.49	1.39	1.34	1.34	1.01	-	1.84	-2.97	1.17	0.51	2.16	2.88	-
	Emissions	Life Cycle Emissions	-1.97	0.55	0.82	0.30	0.33	0.36	0.36	2.12	3.78	0.11	-2.03	0.74	0.46	5.12	4.69	-1.38
		Land & Carbon Stocks	-4.87	2.60	2.82	-	-	-	-	-	3.28	-0.79	-	-1.02	-	-	2.12	0.64
		Counterfactuals	-0.62	-	-0.37	-	-	-	-	-	0.68	-	1.86	-	-	-0.49	2.00	-
	Energy	Replaced Fuels	-	6.20	-	3.83	2.15	4.24	3.10	3.93	5.38	5.48	3.10	4.55	6.46	4.96	3.31	4.02

largely a consequence of identified risks related to *Infrastructure*, *Feedstock Mobilisation* and those of the *Technology* such as efficiencies and techno-economics. Fig. 4 provides valuable insights by highlighting the numerous balances and trade-offs across the framework. For example, despite there being a balance towards overall sustainability risk for Development, there are also multiple Development sustainability Themes where there is potential for attractive sustainability benefits - for the *Economy*, the *Energy Sector*, the *Bioeconomy* and through *Land Utilisation*. SPS scores at the individual Issue resolution are not included within Fig. 4 due to size constraints, these are included in the Supplementary Materials. However, the varying width of bars at the Indicator resolution provides insight into the number of Sustainability Issues attributed to each.

3.2. Results – bioenergy sustainability trends

Figs. 3 and 4 and Table 2 may be used to identify the leading potential sustainability risks and benefits linked to each case study and to highlight consistent trends across case studies. Focusing on the individual case study results highlights both common trends, but also many differences that reinforce the concept that sustainability is not a uniform characteristic across all bioenergy projects - sustainability is not binary concept for bioenergy but a balance of risks and benefits. The results also demonstrate there is potential for both risks and benefits within each of the Categories. However as Fig. 4 demonstrates, the areas identified by the bioenergy experts where there is the greatest potential for sustainability benefits was within the *Climate Change & Emissions* Category and the highest potential risks are identified within the *Development* Category.

Contrasts in how each of Fig. 3's radar graphs are shaded highlights large variations in the extent that different sustainability indicators are deemed relevant to each case study. Inclusion of the 10 *People* sustainability Indicators ranges from 0% (CS14) to 70% (CS2) on average case studies included 33% of these indicators. Inclusion of the 14 *Development* sustainability indicators ranges from 21% (CS3) to 100% (CS12, CS13) with an average of 68%. For the 8 *Natural System* indicators, the range was 0% (CS14) to 63% (CS2), with an average of 34%. For the 6 *Climate Change & Emissions* indicators from 50% (CS3, CS5, CS6, CS7, CS16) to 100% (CS15) with an average of 68%. These results arguably reflect the inherent priorities and knowledge of the bioenergy experts that analysed each case study using the BSIM - individual sustainability issues not being included within the analyses where they are deemed not important or relevant to the case study's sustainability, or potentially where the user has insufficient knowledge of a given issue to include it within their assessment. Assuming the inclusion of sustainability issues reflects the priorities and expertise of bioenergy researchers, the results illustrate that *Development* and *Climate Change & Emissions* sustainability themes are those most uniformly considered important for bioenergy sustainability. In contrast, the results demonstrate a higher degree of variance in the inclusion of *People* and *Natural System* sustainability themes across the case studies – indicating these themes are potentially prioritised less or are less understood [36]. *Whole Life Cycle Emissions*, interactions with *Wider Sectors* and *Processing Efficiencies* were the individual sustainability Indicator most widely included across the case studies. In contrast *Strong Institutions*, *Decent Work* and *Heavy Metals* were the least included individual sustainability Indicators.

The sustainability resolution analysis within Fig. 4 demonstrates that at the Theme and Indicator resolutions, on balance there are far more areas where benefits may be gained than areas of risk. Leading examples include: *Jobs & Skills*, in stimulating *Partnerships* and increasing *Energy Access*, in producing *Added-Value Products* and particularly by leading to *Replaced Fuels*. The leading potential sustainability risks, notably relate to: *Feedstock Mobilisation* (production, mobilisation, distribution), to the *Technology* (efficiencies, techno-economics), for the *Air* (PM pollutants) and for *Emissions* (notably for carbon stocks).

The following sections provide description of the leading trends identified across Fig. 3 case study sustainability maps for different biomass resources, pre-treatment and conversion technologies and bioenergy vectors. Table 3 presents a summary of the leading sustainability risk and benefit trends identified across the case studies.

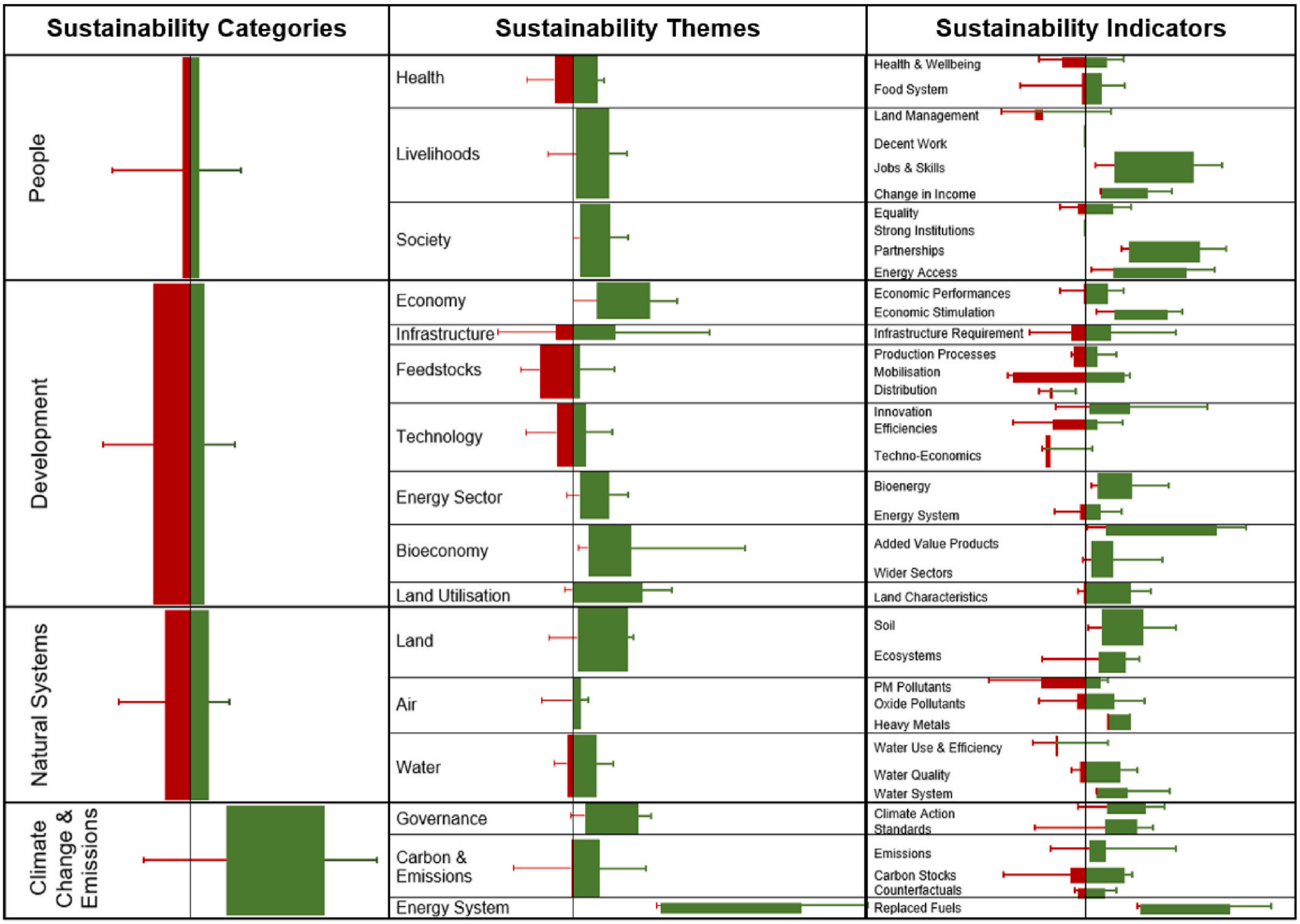

Fig. 4. Range of SPS Values across the Bioenergy Case Studies at each Resolution of the BSIM's Sustainability Assessment Framework. Highlighting the sustainability trade-offs and balances across the case studies. High and low error bars represent the maximum and minimum SPS values across the 16 case studies. Shaded bars represent the 1st and 3rd quartile SPS values across case studies. Bars are shaded red where sustainability risks are calculated and shaded green where sustainability benefits are calculated. Results at the 'Sustainability Issue' resolution are not included, however the width of the bars at the Indicator resolution can provide insight into the number of Issues attributed to each. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.1. Biomass resource trends

3.2.1.1. Imported energy crops. CS1 was developed to provide insight into the sustainability of imported energy crop resources. Fig. 3 radar graph and data within Table 2 clearly highlight the potential sustainability risks for CS1 outbalance the potential benefits. Acute areas of concern include sustainability risks for *Food Systems* and *Land Management*, relating to *Feedstock Distribution* processes and *Supply & System Efficiencies* of the processes, also for *Ecosystems*, and for *Land & Carbon Stocks*. Importing energy crops are also shown to provide a number of potential benefits including *Economic Stimulation* for the production regions, as a result of the feedstock *Distribution* networks, for *Water Systems*, in promoting *Climate Action* and potential benefits for *Land & Carbon Stocks*.

3.2.1.2. Energy crops. Six of the case studies include use of energy crops as feedstocks (CS2, CS3, CS9, CS12, CS13, CS16). In contrast to outputs for imported energy crops (CS1), the potential sustainability benefits of producing/mobilising energy crops as bioenergy feedstocks are shown to outbalance the risks across each sustainability Category. Five of the case studies highlight the leading potential benefit for *People* would be potential *Changes in Income* and three of the case studies also highlighted creation of *Jobs & Skills* as a leading benefit. The majority of the energy crop case studies identify enhanced *Economic Performances* and the 'knock-on' positive influences from the new *Infrastructure Requirements*, and *Utilisation of Land* as the leading potential benefit gained for *Development*.

Several sustainability risks are also identified for *Development*, relating to the *Techno-economic* performances and issues and related to *Feedstock Distribution* and *Supply & Systems Efficiencies*. Whilst potential impacts on Ecosystems were identified as a leading risk in CS-1, the UK energy crop case studies highlight the potential positive benefits for Ecosystems and Soil. This is based on the assumption that energy crops are produced in a sustainable manner such as careful placement in the landscape, although the sustainability risks of poor production practices are very much real as described widely by literature [37,38].

The leading benefit for *Climate Change and Emissions* are identified as *Land & Carbon Stocks*, linked to the potential for energy crops to enhance carbon sinks and to provide carbon savings through the replacement of fossil fuels. Multiple case studies also highlight the importance of *Counterfactual Considerations* when considering emissions and carbon stocks, providing both a potential risks and/or benefits depending on circumstances of counterfactual activities [39].

The sustainability case for producing energy crops on marginal vs agricultural lands may be analysed by comparing the sustainability maps for CS2 (miscanthus on marginal land) with CS3 and CS9 (willow

Table 3

Sustainability Risk & Benefits Consistently Identified across the 16 UK Bioenergy Case Studies. Leading sustainability risks and benefits identified across the case study sustainability maps for different biomass resources, pre-treatment and conversion technologies and bioenergy vectors.

UK Bioenergy Case Study Dynamics		Sustainability Risks	Sustainability Benefits
Biomass Resources	*Imported Energy Crops*	*Food Systems/Land Management/Feedstock Distribution/Supply & System Efficiencies/Ecosystems/Land & Carbon Stocks*	*Economic Stimulation/Feedstock Distribution/Water Systems/Climate Action Land/Carbon Stocks*
	Energy Crops	*Techno-economic/Feedstock Distribution/Supply & Systems Efficiencies/Counterfactual Considerations*	*Changes in Income/Jobs & Skills/Economic Performances/Infrastructure Requirements/Utilisation of Land/Ecosystems/Soil/Land & Carbon Stocks/ Counterfactual Considerations*
	Wastes	*Feedstock Distribution/Innovation/Water Use & Efficiency/ Water Quality*	*Economic Stimulation/Innovation/Water Use & Efficiency/Water Quality*
	Agri & Forestry Residues	*Infrastructure Requirements/Supply & System Efficiencies/ Techno-economics*	*Jobs & Skills/Changes in Income/Water Systems/Land & Carbon Stocks/ Economic Stimulation/Innovation*
	Seaweed	*Water Use & Efficiency/Water Quality*	*Economic Stimulation/Innovation*
Pre-treatment & Conversion	*Thermal Processes*	*Supply & System Efficiencies/Techno-economics/Infrastructure Requirements/Innovation/Whole Life Cycle Emissions/ Counterfactual Considerations*	*Energy Access/Jobs & Skills/Economic Stimulation/Replaced Fuels/Whole Life Cycle Emissions/Counterfactual Considerations*
	Catalytic Processes	*Techno-economics/TRLs/Water Use & Efficiency/Water Quality*	*Jobs and Skills/Energy Access/Economic Stimulation/Infrastructure Requirements/Added Value Products/Water Use & Efficiency/Water Quality/ Whole Life Cycle Emissions/Replaced Fuels*
	Carbon Capture & Utilisation	*Infrastructure Requirements/Supply & System Efficiencies/ Techno-economics/Economic Stimulation/Counterfactual Considerations*	*Climate Action/Standards/Innovation/Infrastructure Requirements/Economic Stimulation/Whole Life Cycle Emissions/Replaced Fuels*
Bioenergy Vectors	*Liquid Fuels*	*Infrastructure Requirement/Supply and System Efficiencies/ Techno-economics/Innovation*	*Jobs & Skills/Change in Income/Energy Access/Economic Stimulation/Added Value Products/Air Quality/Whole Life Cycle Emissions/Replaced Fuels/ Innovation*
	Gases	*Infrastructure Requirement/Supply and System Efficiencies/ Techno-economics/Innovation*	*Energy Access/Infrastructure Requirement/Particulate Matter Pollutants/Oxide Pollutants/Replaced Fuels/Whole Life Cycle Emissions*
	Heat and Power	*Infrastructure Requirement/Supply and System Efficiencies/ Techno-economics/Innovation*	*Whole Life Cycle Emissions/Replaced Fuels*
	Products & Chemicals	*Infrastructure Requirement/Supply and System Efficiencies/ Techno-economics/Innovation/Particulate Matter Pollutants*	*Economic Stimulation Added Value Products/Whole Life Cycle Emissions*

and miscanthus on agricultural land respectively). Use of marginal lands is shown to provide both risks and benefits to a wider range of indicators. This finding reflects existing studies [40] that identify potential for risks and/or benefits for *Ecosystems* depending on the circumstances and notable greater potential risks for *Water Use & Efficiency*. Also increased potential benefits for *People* (e.g. *Food System & Land Management*) and for *Development* (e.g *Economic Stimulation*, *Feedstock Mobilisation*, *Feedstock Distribution*).

3.2.1.3. Wastes. Four case studies focus on UK waste materials including wastewaters (CS4, CS5) waste wood from industry (CS6) and food wastes (CS10). Many of the sustainability risks and benefits of using wastes as a feedstock are linked to *Development*. The leading sustainability benefits includes the potential *Economic Stimulation* generated as a result of waste bioenergy schemes, whilst *Feedstock Distribution* is identified as a leading area of risk. *Innovation* is highlighted across the waste case studies as an area of interest for sustainability, as advanced energy from waste technologies require further development to allow widespread deployment, although if achieved - wider sustainability benefits may be gained. Potential risks and benefits to *Water Use & Efficiency* and *Water Quality* are highlighted as a notable *Natural Systems* sustainability issue for the waste Case studies - potential benefits are shown to outweigh the risks.

3.2.1.4. Agri & forestry residues. The results in Table 2 for the case studies that utilise agri and forestry residues as feedstocks (CS13, CS14, CS15), identify potential sustainability benefits for *People*, *Natural Systems* and for *Climate Change & Emissions*. Leading benefits include the creation of *Jobs & Skills* and *Changes in Income*, potential benefits for *Water Systems* and for carbon and emissions through positive influences for *Land & Carbon Stocks* – reflecting existing findings in literature where sustainable forest management and residue utilisations practices are applied [41].

The leading sustainability risks for the agri and forestry residue case studies as highlighted in Table 2 are *Development* issues. *Infrastructure Requirements*, *Supply & System Efficiencies* and *Techno-economics* – each representing key barriers that will reduce the viability of agri and forestry residue projects. Where these barriers can be overcome, the case study results highlight potential benefits for *Development* including *Economic Stimulation* for wider sectors and resulting from *Innovation* resulting from increased mobilisation of these resources.

3.2.1.5. Seaweed. CS7 allows insight into the sustainability performance of seaweed as a feedstock. Notable outputs include the absence of the land and food system issues that have relevance for the terrestrial feedstocks. Leading risks include potential impacts for *Water Use & Efficiency* and *Water Quality* linked to the processing and onward use of the feedstock [42]. Potential benefits include *Economic Stimulation* resulting from the *Innovation* that will be necessary to produce/mobilise these feedstocks at scale.

3.2.2. Pre-treatment & conversion trends

3.2.2.1. Thermal processes. Many of the case studies include thermal pre-treatment and conversion processes, including pyrolysis (CS10, CS11) gasification (CS4, CS14, CS15) and direct combustion through combined heat and power technologies (CS9). Sustainability trends across these case studies can be observed in each sustainability Category. For *People* the potential of increasing *Energy Access* and new *Jobs & Skills* is shown to be a leading benefit. Overall benefits are also highlighted for *Climate Change & Emissions*, where the leading benefit is the potential to *Replace Fuels* with low carbon bio-alternatives. The bioenergy experts identify the sustainability benefits for *Whole Life Cycle Emissions* and the *Counterfactual Considerations* for these case studies outweigh the potential risks; albeit risks are identified, and measures may be needed to ensure the projects result in genuine reduction in emissions.

The case studies identify a series of *Development* sustainability risks, notably related to *Supply & System Efficiencies* and the *Techno-economics*. *Infrastructure Requirements* and *Innovation* are identified as both leading risks and benefits, potentially reflecting the need for large investments in infrastructure, skills and knowhow to enable these projects - albeit if deployed and linked with the UKs existing energy infrastructure large potential benefits may be gained. Where risks and barriers can be mitigated the thermal process case study results also highlight large potential benefits for the *Economic Stimulation* of wider sectors.

3.2.2.2. Catalytic processes. Catalysis processes are included within many of the case studies to pre-treat and convert the feedstocks, including chemical catalysis (CS4, CS12), photocatalysis (CS5, CS16) and use of ionic liquids (CS13). Similar trends can be observed across both the thermal process and catalysis case studies. For example, the potential for creation of *Jobs and Skills* and increasing *Energy Access* are the leading potential benefits for *People* and the potential to *Replace Fuels* with low carbon bio-alternatives is the leading potential benefit for *Climate Change and Emissions*. Key differences identified within the catalysis case studies include reduced potential risks for *Whole Life Cycle Emissions* and the presence of water sustainability issues. The chemical catalysis case studies are shown to provide both potential risks and benefits for *Water Use & Efficiency* and *Water Quality*, depending on the nature of the catalysts used and how they are managed [43]. For CS13 where ionic liquids are used, a potential benefit is identified for *Water Quality* as this technology may replace existing activities such as pulping processes that have environmental impacts including risks of water contamination [44].

The *Techno-economics* and issues related to *Innovation* such as the current TRLs are shown to be leading sustainability risks for catalysis. Again, reflecting the trends of the thermal conversion case studies, where these barriers can be overcome there is large *Economic Stimulation* potential for wider sector. In contrast with the thermal process case studies, *Infrastructure Requirements* of catalysis projects are shown to be a much-reduced sustainability risk and the production of *Added Value Products* is a leading sustainability benefit for *Development*.

3.2.2.3. Carbon capture & utilisation trends. Half of the case studies include carbon capture storage (CCS) and/or carbon capture and utilisation (CCU) processes. The benefits of these activities are most evident within the *Climate Change & Emission* category where the bioenergy experts clearly identify the benefits outweighing risks in potentially promoting *Climate Action*, benefits from use of technical and fuel *Standards*, for *Whole Life Cycle Emissions* and most notably through the *Replaced Fuels*. However, multiple case studies also identify emission risks notably related to the Counterfactual Considerations - highlighting these technologies may not guarantee net negative emissions by default and with variation in the carbon dioxide removal potential, focus will be required to ensure the negative emission performances of these projects [34].

Within the *Development* sustainability Category, a series of notable risks are identified that will likely influence the viability of projects, including the *Infrastructure Requirements*, risk related to *Supply & System Efficiencies*, *Techno-economics* and particular potential risks for *Economic Stimulation* of wider economic sectors. Where these barriers are overcome and technologies deployed there may be leading benefits for *Innovation* potentially through commercialisation of the technologies, for *Infrastructure Requirements* gained through using existing energy and chemical infrastructure and for *Economic Stimulation* once CCS and or CCU technologies are proven and widely deployed [45].

3.2.3. Bioenergy vector trends

3.2.3.1. Liquid fuels. Four case studies (CS10, CS13, CS14, CS15) produce a range of liquid fuel products appropriate for different energy and transport sector end uses. The results for these case studies presented in Table 2 highlight a consistent trend where the bioenergy experts identify a balance towards greater benefits for *People*, *Natural Systems* and *Climate Change & Emissions*, albeit with areas of acute risk related to *Development* sustainability issues. Leading benefits are highlighted for *Jobs & Skills*, *Change in Income*, *Energy Access*, and the potential reduction of *Whole Life Cycle Emissions*, and through *Replaced Fuels*. A further notable potential benefit is identified for Air Quality– combustion of biofuels in place of fossil fuels can result in fewer emissions such as sulphur dioxide, particulates and air toxics [46]. Leading potential sustainability benefits for *Development* are the *Added Value Products*, the positive influence of *Innovation* and the *Economic Stimulation* potentially gained by wider sectors resulting from greater use of low carbon biofuels. Identified risks for the liquid fuel case studies include the *Infrastructure Requirement*, *Supply and System Efficiencies*, the *Techno-economics* and the *Innovation* that will be required to increase the viability of such projects.

3.2.3.2. Gases. Five of the case studies (CS8, CS10, CS11, CS14, CS16) produce a range of singular or multiple gas products, including hydrogen and biomethane. Similar overarching trends can be observed in the results with potential benefits for *People* and *Climate Change & Emissions* and areas of both acute risk and benefit related to *Development*. A notable exception are the potential benefits of the *Infrastructure Requirement* of these vectors, likely reflecting potential compatibility with the UK existing gas grid infrastructure.

Analyses of results for CS8 in Fig. 3 and Table 2, provides particular insight into the sustainability dynamics of hydrogen and specifically the risk and benefits of green hydrogen (produced from biomass feedstocks) compared to blue hydrogen (produced from fossil fuel feedstocks). The CS8 radar graph highlights the leading potential benefits for *People* may be increased *Energy Access*. While the benefit for *Climate Change & Emissions* will be providing low carbon *Replaced Fuels* in addition to the potential benefits from the *Whole Life Cycle Emissions* performances. In contrast to many of the other case studies, CS8 also identifies potential benefits for air quality linked to reduced *Particulate Matter Pollutants* and *Oxide Pollutants* where hydrogen potentially replaces higher polluting fuels. *Infrastructure Requirements* are also shown to represent both a high benefit linked to the UK's existing gas infrastructures and a high risk linked to the extensive upgrades that may be required to transition to hydrogen vectors [47].

3.2.3.3. Heat and power. Two case studies (CS14, CS16) include analysis of heat and/or power generation as part of the sustainability assessment of a whole value chain. In comparison to many of the case studies that produce added value fuels and chemicals, these sustainability maps are less complex. The leading potential sustainability benefits are highlighted as *Whole Life Cycle Emissions* and *Replaced Fuels*, reflecting the fossil fuel technologies these case studies would be replacing. High risks and benefits are also highlighted for *Infrastructure Requirements,* potentially reflecting the existing compatibility with the UK's existing energy infrastructure and complexities of deploying these projects at scale.

3.2.3.4. Products & chemicals. Four of the case studies generate non-energy vectors and biomaterials including biochar (CS10, CS11, CS12, CS13) and platform chemicals (CS12, CS13). The sustainability maps for *People, Development, Natural Systems* and *Climate Change & Emissions* reflect that of many of the case studies described above. Notable dynamics specific to these case studies include the potential risk for air quality from *Particulate Matter Pollutants*, also the potential benefits that may be gained for *Development* through provided *Added Value Products*.

3.3. Influence of the bioenergy case studies on the UN Sustainable Development Goals

Fig. 5 presents outputs from the BSIM mapping the potential influence the case studies may have on each of the 17 SDGs. As each SDG is a construct of multiple individual sustainability targets, there is potential for a given project to have both a positive and negative influence on an

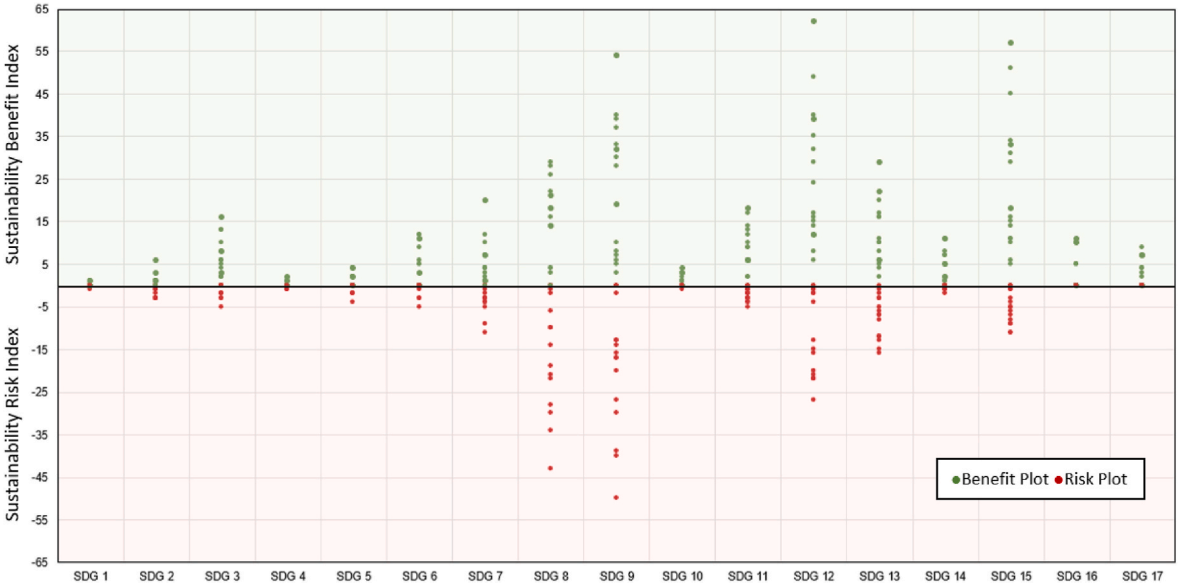

Fig. 5. Mapping the Potential Influence of the Bioenergy Case Studies on the United Nations Sustainable Development Goals (SDGs). Sustainability Risk Index and Sustainability Benefit Index values are calculated using the BSIM for each SDG, reflecting the judgement of the bioenergy researchers responsible for modelling respective case studies.

SDG depending on how they influence the individual targets. The BSIM maps the potential links between the 126 issues of the BSIM's Sustainability Assessment Framework with all the individual targets of the SDGs. Where a potential sustainability benefit/risk is identified for a given issue, the BSIM's calculations assume there will be a corresponding benefit/risk in achieving SDG targets linked to that issue. Two Sustainability Index values are calculated for each SDG – a Sustainability Benefit Index (SBI) value reflecting the extent a given project may provide benefit for achieving each SDG, and a Sustainability Risk Index (SRI) value reflecting potential risk. The index values are a tally of the number of BSIM's issues that are identified as having either a positive or negative influence on each SDG. For example, a project's SBI for a given SDG will be 10 where 10 sustainability issues have been identified as providing a positive influence on the targets of the SDG.

The SBI and SRI plot values for each case study are presented in Fig. 5 These represent the potential influence each case study may have on the SDGs judged by the bioenergy researchers who modelled the case studies. A full breakdown of the values are included in the Supplementary Materials and the method for assessing the potential influence of projects on the SDGs is discussed further within the BSIM's Guidance Manual [19].

Fig. 5 shows that the case studies have the potential to have both positive and negative influences on the 17 SDGs. The SDGs where the bioenergy case studies may generate notable potential benefits are for SDG 3 (Good Health & Well-being), SDG7 (Affordable & Clean Energy), SDG11 (Sustainable Cities & Communities), SDG12 (Responsible Consumption & Production), SDG13 (Climate Action) and SD15 (Life on Land). There are no SDGs where the potential risks to achieving an SDG far exceeds the benefits that may be gained. However there are SDGs where there is close parity in the potential risk and benefit, with potential for the largest risks for SDG8 (Decent Work & Economic Growth) and SDG9 (Industry Innovation & Infrastructure).

4. Discussion

4.1. *Overarching bioenergy sustainability trends & implications for decision makers*

Despite the many differences between the sustainability performances of the research's case studies, the results highlight sustainability trends that are consistent across different feedstocks, technologies, vectors etc. The research identifies trends of sustainability benefits for *People* (jobs & skills, changes in income, partnerships, energy access); for *Development* (economy, energy sector, bioeconomy, land utilisation); for *Natural Systems* (soil, heavy metals, waste system); and, for *Climate Change & Emissions* (climate action, replaced fuels). The research also identifies consistent risk trends for *People* (health & wellbeing, land management); for *Development* (infrastructure, feedstock mobilisation, technology techno-economics and efficiencies); for *Natural Systems* (oxide and PM air pollutants, water use & efficiency); and, for *Climate Change & Emissions* (emissions, carbon stocks).

4.1.1. *Mitigating sustainability risks to increase the viability of bioenergy*

As highlighted by Fig. 4 there is potential for sustainability risks across the BSIM sustainability assessment framework. The greatest areas of concern are where consistent risk trends are identified, where the risks far outbalance any potential benefits and particularly where the potential risks may undermine the viability of a project. This research finds the leading areas of concern within the *Development* category where sustainability risks may influence technical, practical and economic viability – a cocktail that will restrict the chances of any renewable energy project gaining the investment it requires [48]. Also within the *Climate Change & Emissions* category where poor performance has the potential to undermine a principal objective of bioenergy – to provide low carbon energy [49].

4.1.1.1. Techno-economic performance risks & potential mitigations. The techno-economics of bioenergy projects are a vital theme that will ultimately determine whether bioenergy can compete and replace established conventional energy technologies. Projects will achieve stronger economic performances where there is efficient use of biomass resources, where energy or fuels are produced alongside added-value products and where circularity is built into schemes for example where 'waste' materials become commodities [50]. This theme is reflected in the outputs of this research, for example CS12 and CS13 both generate added value products such as platform chemicals – Fig. 3 radar graphs highlight notable potential benefits for *Development*, including for *Economic Performance* and *Economic Stimulation*, and through *Complementing Wider Sectors* of the economy.

Historically, new energy technologies have needed decades to mature [51] and achieve transformative impacts, however the development trajectories of renewable energy technologies have been breaking this paradigm. Driven by decarbonisation targets, big finance and with tech companies now on board, there is the potential for acceleration of transitions and for the benefits from actions to filter down from the national to the regional to the company and even to the individual household scale [52]. Sustained research and investment has the potential to reduce many of the *Development* sustainability risks, and it is in the interest of companies and entrepreneurs to reduce costs and increase efficiencies to enhance economic competitiveness of bioenergy systems [53].

There is also much policy makers could do to reduce the barriers for renewable technologies and 'level the playing field' with established fossil fuel technologies [54]. For example: developing financial instruments and organisations focused on renewable energy project financing [55]; developing financial mechanisms that reduce the high initial capital costs of bioenergy projects to entice investors [56] – high capital costs and payback periods making many projects economically unattractive to investors [57]; reducing the subsidies provided to conventional energy technologies, IRENA (2020) calculated that globally the direct subsidies for fossil fuels exceeded subsidies for renewable energy by a factor of 19 [58].

The techno-economics of carbon capture storage (CCS) and/or carbon capture and utilisation (CCU) technologies is consistently identified as a leading area of potential risk across the case studies where these technologies are included. The efficiencies and performances of such activities will improve as technologies mature, although the economics of storage or utilisation of carbon will continue to be influenced by wider carbon or CO_2 commodity prices respectively. Although widely predicted to change, current prices are substantially lower than what would be required to make 'CCUS' processes economically viable without support [59]. However there is also a strong argument such as made by Baylin-Stern and Berghout (2021) that "the idea that CCUS is high cost ignores the bigger picture", as by constricting performance in economic terms ignores the unique strengths of these technologies and their potential to be mainstream decarbonising solutions [60].

4.1.1.2. Feedstock mobilisation & product distribution risks & potential mitigations. The production, mobilisation and distribution of feedstocks and products is a risk theme identified across many of the case studies and for each category of biomass resource assessed. For CS4, 10, 12 and 15 bioenergy researchers identify this as the leading *Development* sustainability risk. Biomass resource modelling exercises often highlight large ranges of 'potential resource availabilities', the scale of these ranges provide an indication of the effort that may be required to mobilise upper limits of available resource [61]. There is also considerable ongoing uncertainty in the realistic levels biomass that may be available for specific bioenergy schemes [62].

There are many factors that will influence the sustainable limits of resource availability [63], common trends include the spatial distribution of the resources, its bulk density that will influence transport techno-economics, the distances and available infrastructure connecting resources, processing sites and end use [64]. There are also further barriers that prevent/slow the development of supply chains including the capital burden of starting new production lines and infrastructure. To mobilise feedstocks at a large national/international scale and ensure efficient movement of biofuels and products, efficient production and supply chains are needed at the 'local scale' where key activities take place [65]. Support should potentially target actions that help build the local foundations that may collectively enable larger enterprises. For example: support for local actors to promote their participation and access to markets; research and support schemes that promote supply chain efficiency and economics; and specific support that mitigates stakeholder and investor risk in order to bolster confidence [66].

4.1.1.3. Emissions & carbon stock risks & potential mitigations. The research highlights both consistent and sometimes varying trends for *Climate Change & Emissions* between the different resource categories, particularly risks relating to carbon stores and flows. All the UK case studies demonstrate the substantial benefits for emissions/carbon potentially gained through bioenergy projects, but there are also consistent risks. Potential risks for carbon are shown to be most pronounced for the energy crop case studies and much less so for the residue and waste case studies - reflecting the potential for release of carbon if land use change occurs or if land is used unsustainably [39]. The sustainability outputs for CS2 show the risks and benefits may be amplified where marginal lands are used [67].

Bioenergy sustainability criteria already place much focus on land and protection of carbon stocks. To mitigate potential risks further, comprehensive policies and management guidelines should be developed/implemented that: ensure avoidance of high carbon soil such as peats; restrict conversion of land uses (such as perennial grassland or forestry) to energy cropping; ensure only sustainable levels of residues are taken from the land, and; return suitable post-conversion materials to soils [68].

4.1.2. Maximising sustainability benefits to drive sustainable development

Fig. 4 highlights the many sustainability themes where bioenergy may benefit *People*, *Development*, *Natural Systems* and *Climate Change & Emissions*. There are a number of themes where the analyses highlight broad sustainability benefits that far exceed the identified risks - these should be promoted and projects and policy frameworks should be developed to ensure that potential benefits are achieved and maximised.

4.1.2.1. Potential benefits for jobs, skills and local economies. A common trend identified across case studies regardless of feedstock used or technologies applied, is the potential benefits for creation of jobs, skills and for the economy. Through providing low carbon alternative energy and fuels, bioenergy can provide multiple benefits for people and economic development [69]. This is evidenced throughout the results and particularly within Fig. 5 where the case studies are shown to provide positive influences on the targets underpinning SDG 3 (Good Health & Well-being), SDG7 (Affordable & Clean Energy), SDG11 (Sustainable Cities & Communities) and SDG12 (Responsible Consumption & Production). This supports statistics from recent years that reflect rapid increases in jobs in the renewable energy sector, a trend that is expected to continue [70]. Employment within the bioenergy sector is shown to exceed that of other renewable technologies as a consequence of the additional unique work elements of bioenergy related to feedstock production, supply, handling and logistics – the bioenergy sector offering a valuable opportunity to drive economic growth and job creation [71]. Benefits of jobs and for stimulation of economic sectors is a trend not limited to UK case studies analysed in this paper - previous sustainability mapping research [9] using the BSIM to analyse the sustainability of bioenergy generated from coffee residues in rural Colombia found overwhelming benefits for people, society and the economy, and widespread positive influence on the individual targets of the SDGs. The International Renewable Energy Agency (IRENA) [72] argue that providing support for small and medium enterprises is the best way to drive deployment of technologies in a way that provides maximum local economic benefits.

4.1.2.2. Mitigating the land systems risks & realising the benefits from energy crops. The direct impacts of producing dedicated energy crops on soil carbon and GHG emissions are increasingly well understood, and a growing body of research highlights a consistent with significant trend of lifecycle GHG mitigation where energy crops replace conventional fuels [73]. There is less consensus across literature when assessing the wider sustainability implications of large scale energy crop production [74]. A global assessment by Tudge et al. (2021) concluding that "biofuel crops have a negative effect on local species richness and total abundance, and that traditional first-generation biofuels are especially damaging, causing large declines in vertebrate abundance and plant species richness" [75]. This is reflected in the research findings for CS1, where imported energy crops are shown to reflect far greater potential for sustainability risks rather than benefits. Leading potential risks are linked to feedstock production processes where there are implications for land systems (risk for carbon and biodiversity etc) and linked to land utilisation (risks for ownership, for food systems etc). This justifies the need and argument for sustainability criteria and schemes that focus on restricting how lands are used to produce energy crops destined for international trade.

In contrast the bioenergy case studies that included use of UK grown energy crops highlighted a trend of potential benefits for land systems (carbon, biodiversity etc). This is also reflective of a growing body of research including by Donnison et al. (2021) who measured up to 75% increases in biodiversity, 81% increases in bird abundance and 100% increase in bird species richness where previous food-based agricultural land was used to grow energy crops [76]. The results for CS2, highlight that use of marginal land to grow energy crops could deliver the same but intensified sustainability benefits and risks. Marginal lands potentially providing lower starting benchmark performances for soil carbon, biodiversity etc, and therefore there is greater potential for improvement. Although the potential for risks is also shown to be greater where marginal lands are used [67].

This research provides further evidence of the social, economic, environmental and climate benefits that may be gained through energy crops, whether these benefits are accrued will likely depend on site specifics: location, soil, feedstock choices, land management etc. Support for stakeholders such as guidance materials and supportive policy framework would help maximise potential benefits and help avoid unintended consequences [38].

4.1.2.3. Mitigating risks and maximising the potential benefits of/for infrastructure. Of the themes included within the BSIM's sustainability assessment framework, Fig. 4 highlights infrastructure as a potential issue that may provide equally high potential risks and benefits for bioenergy projects. The risk potentially reflecting the high capital cost and environmental impacts of new infrastructure projects [77]. Levidow & Papaioannou (2015) argue existing energy infrastructure represents a potential risk for any renewable energy projects, as may generate a 'lock-in' effect that can restrict required transitions; and in turn continued long term use of existing infrastructure may risk the continued environmental costs of existing energy systems [78]. This may include a lock-in to physical infrastructure such as power plants, grids, supply chains etc; to institutional processes such as economic, social and political groups and stakeholders that may resist change, and; behavioural lock-ins such as social norms and cultural values that further resist any potential changes required [79].

Bioenergy differs from most other renewables in that it may be highly compatible with existing infrastructure. Large sustainability benefits may be gained, and energy transitions may be accelerated where existing infrastructure can be repurposed, such as: use of existing pipeline for biofuels; adapting supply chain infrastructure for feedstocks or biofuels; or converting power stations to co-fire or become dedicated bioenergy sites. The Institute of Civil Engineers (ICE) believe much of existing infrastructure will still be in service by 2050, therefore any decarbonisation plan should equally explore opportunities to use existing infrastructure in addition to targeting new projects [80].

4.1.2.4. Potential benefits from low carbon energy, fuels & products. The research highlights consistent sustainability benefits that may be gained where projects generate low carbon energy to replace conventional energy systems *(Replaced Fuels*) and where projects produce added-value products such as bio-chemicals (*Added Value Products*). Amplification of benefits may be gained where projects generate both energy and products, for example as shown in Fig. 3 for CS13 where platform chemicals, biofuels and biochar are all produced. This provides potential opportunities for wider economic sectors whilst also improving the economic performances of projects [81].

4.1.2.5. Focus on bio-hydrogen. The research case studies that produce hydrogen as either a primary or secondary product provide a valuable example of how widespread sustainability benefits may be gained where targeted actions can overcome the risks and barriers that may be slowing technology deployment. The hydrogen case studies unanimously highlight the potential benefits for climate change though replacing fuels, for society through increasing access to low carbon energy, and for natural systems through reducing air pollution. Each of these mapped benefits reflect hydrogen's value as an energy carrier, its potential to replace fossil fuels and generate zero emissions at the point of use; its potential to be stored and transported in either liquid or gaseous, and its flexibility to be either directly combusted or used in fuel cells to generate heat and electricity [82]. Although these benefits may only be gained by mitigating the consistent risks as highlighting by the sustainability mapping for CS8 – upgrading infrastructure, improving process efficiencies and techno-economics, and ensuring efficient and economically viable feedstock supply chains. As discussed previously and as recommended by Saratale et al. (2019) [83] this may be achieved by developing a supportive policy framework and continued investment in research and development to improve technical efficiencies and economic performances.

4.1.2.6. Focus on catalysis. Various catalysis processes are included across the many of the research case studies. This reflects the important role of catalysis for our economies and society, Catlow et al. (2016) estimating that catalysis is involved at some point in the processing of over 80% of all manufactured products [84]. Potentially the leading findings from analysis of the catalysis case studies is the potential reduced risk of *Whole Life Cycle Emissions* when compared to case studies that don't include catalysis processes - catalysis potentially enabling desirable chemical reactions to take place at much lower temperatures than under the usual thermally activated conditions [85]. Also, the potential economic benefits that may be gained by multiple sectors through production of the *Added Value Products* generated through catalytic processes – catalysis providing alternative highly efficient routes for producing complex molecules with high selectivity at a reduced cost [86]. The research finds a leading risk for the greater deployment of catalysis technologies is the development status (*TRL*) of these technologies and current limited integration into established processes. The UK Knowledge Transfer Network (2021) acknowledge that this may be achieved through increased investment, collaborative research and development activity, increasing access to catalysis capability and establishing demonstrator projects [87].

4.2. Implications of the varying characteristics of bioenergy sustainability

This research finds that 'bioenergy sustainability' is a broad term and is more a dynamic construct than set destination. Different sustainability assessment schemes and tools each evaluate different lists of indicators, in the case of the BSIM applied in this research the sustainability of the bioenergy is assessed against up to 126 different sustainability issues. The consequences of this approach are reflected throughout the results: Fig. 2 highlights the wide-ranging characteristics of the research's 16 bioenergy case studies, whilst; Fig. 3 demonstrates differences in the indicators that are selected and applied by the bioenergy researchers to assess and define sustainability based on their assessment of the boundaries of each case study. The sustainability framework used to assess each case study within this research is bespoke, tailored to the dynamics of each case study – having potential implications for how bioenergy sustainability is assessed and benchmarked.

Focusing on some of the overall trends identified across the case study results, it may be legitimate to ask - are bioenergy projects sustainable if they provide jobs and reduced emissions albeit at the risk of unsustainable feedstock supply chains and techno-economics? Or focusing on the specifics of CS6 and CS7 (Fig. 3), are these case studies sustainable if they provide climate change benefits through replacing fossil fuels and stimulation of wider economic sectors, albeit at the cost of sustainability risks for water systems?

The analysis presented here demonstrates that often there is a dichotomy between different aspects of sustainability across and within different bioenergy pathways. For example, some pathways benefit the wider economy and society while having substantial environmental risks (e.g. CS6 and CS7). The assessment presented here can identify such synergies and trade-offs. It is then the role of society to consider within the specific context at which the bioenergy system is operating, how to balance those trade-offs in terms of which are acceptable.

4.3. Considerations for decision makers

4.3.1. What are the bioenergy sustainability certainties and uncertainties?

Research into biomass and bioenergy themes has taken place over many decades, although has increased exponentially with the rise in prominence of climate change and renewable energy [36]. The growing body of bioenergy literature has contributed to a foundation of knowledge that over the years has significantly reduced many of the uncertainties that previously overshadowed bioenergy projects. For example Whitaker et al. (2017) reported that over the last decade there has been a considerable body of field, laboratory and modelling research that has addressed many of the previous uncertainties concerning perennial bioenergy crops in relation to direct land use change and emissions resulting from crop cultivation [73].

Outputs from this research further contribute reaffirming the knowledge base and reducing bioenergy sustainability uncertainties. Table 4 has been developed to highlight the leading areas of bioenergy sustainability concern as characterised by their inclusion in regulations and legislation, including: the sustainability criteria of the EU's Renewable Energy Directive [13]; the updated RED criteria for forest biomass [88], also; the 2021 Biomass Policy Statement developed by the UK Department for Business, Energy & Industrial Strategy (BEIS) [89]. Table 4 also suggests the remaining levels of uncertainty as identified through and this paper and wider research. Thus, allowing assessment of where future actions should focus and to highlight where narratives based on the evidence should be built to ease the sustainability concerns of wider stakeholders.

4.3.1.1. Applicability of research findings beyond the UK case studies. The BSIM provides flexibility that allows assessment of projects in any country. Although to complete the sustainability mapping of the case studies presented in this research, the respective weightings of sustainability issues in the BSIM were calibrated for the UK. These were determined through an extensive UK stakeholder engagement process [9] and are listed in the Supplementary Materials. These weightings insure that different sustainability issues were credited with influence reflective of current UK priorities and characteristics. A similar 'weighting allocation process' would have to take place for the BSIM to accurately reflect conditions in other countries, and likewise consideration of the UK weightings is required when interpreting the results presented in this paper. Weightings have the influence of 'nudging' performances, therefore the specific BSIM outputs, sustainability maps and trends presented in this research will likely be consistent for projects based in similar contexts.

Table 4
Certainties & uncertainties of leading bioenergy sustainability concerns.

Sustainability Concerns	Assessment of Certainty	Lessons from this Research
Land Use Choices [88,90]	***High Certainty*** *- land use criteria from which biomass can be sourced is central to bioenergy sustainability regulations.*	• UK energy crop case studies identified broad potential sustainability benefits where land is utilised, particularly in the case of marginal lands. • Concerns for imported feedstocks where there may be insufficient regulations that identify which/how lands are utilised [19].
Sustainable Harvest Limits [13]	***Certainty*** *- existing legislation requires sustainability harvesting limits.* ***Uncertainty*** *– specific harvesting limits are often linked to operational 'best practice' that will vary with location characteristics* [91].	• UK Case Studies did not identify any leading risks linked to resource mobilisation, soil health or ecosystems
Waste Hierarchy Principals [89]	***High Certainty*** *– existing legislation provides a clear frameworks for classifying wastes and how they can be managed* [92]. ***Uncertainty*** *– potential for the waste hierarchy to be challenged in the future to prioritise use of waste streams to generate fuels* [93].	• Case Studies identify potential economic stimulation where wastes are used within bioenergy schemes. • Case Studies identify the mobilisation and distribution of waste feedstocks as a sustainability risk for projects.
Technology Efficiencies [13]	***Certainty*** *– existing regulations include minimum energy efficiency requirements.* ***Uncertainty*** *– efficiency limits are conservative compared to achievable levels* [94] *and do not cover of wider system/technology efficiencies* [95].	• Supply chain, system and technology efficiencies are highlighted as a leading sustainability risk across many of the Case Studies. • Case Studies where catalysis processes are applied highlight potential benefits gained through improved efficiencies.
Air Quality [89]	***High Certainty*** *– existing air quality standards require adherence to benchmark performances* [96].	• Air quality was not identified as a leading risk for any Case Study. • Where Case Studies considered the replacement of fossil fuels, benefits for air quality are identified.
Soil Health & Soil Carbon [13]	***Certainty*** *– protection of soil health and carbon are a baseline mandatory requirement of existing bioenergy sustainability schemes.* ***Uncertainty*** *- Concerns persist of how soil is measured and monitored* [11].	• Soil health was not identified as a leading risk for any UK Case Study. • The UK energy crops case studies identified a potential benefit of maintaining and enhancing soil health.
Protection of Biodiversity [13,88]	***High Certainty*** *- protection of ecosystems and biodiversity are a baseline mandatory requirement of existing bioenergy sustainability schemes.* ***Uncertainty*** *– persisting concerns for imported feedstocks, reliant on strength of local regulations, enforcement and chain of custody* [97].	• The UK energy crops case studies identified a potential benefit for ecosystem biodiversity.
GHG Emission Performances [13,88,89]	***High Certainty*** *– achieving GHG emission performance benchmarks below that of*	• Case Studies overwhelmingly demonstrate the potential

(*continued on next page*)

Table 4 (*continued*)

Sustainability Concerns	Assessment of Certainty	Lessons from this Research
	comparators is a primary criterion across bioenergy sustainability regulations. A large and growing body of research demonstrates bioenergy can provide reduced emissions compared to fossil fuels [98]. *Research finds energy crops will provide low carbon energy and fuels as long as best practice/regulations are applied when selecting and managing land; and for wastes and residues reliant on sustainable limits of feedstock utilisation and use of efficient technologies applied* [39]. ***Uncertainty*** *– persistent concerns of the accuracy of measuring, reporting and monitoring emissions and assumptions applied for counterfactual baselines* [99].	GHG reduction benefits gained far exceed potential risks. • Case Studies also highlight a persistent risk of GHG emissions, indicating importance of strong institutions and adherence to best practice to minimise and where possible mitigate emissions.
Co-benefits [89]	***Uncertainty*** *– need to ensure bioenergy schemes are developed to provide broad sustainability benefits.*	• Each UK bioenergy case studies identifies substantial sustainability benefits that may be gained for people, for development, for natural systems and the climate.

4.3.2. How appropriate are existing bioenergy sustainability assessment frameworks?

Environmental problems are typically extremely complex and scientific methods have a tendency to focus on individual issues rather than enable understanding of the intricate webs of interactions, opting to improve understandings of the 'whole' rather than its constituent parts [100]. When applied to sustainability analyses, tools and assessment frameworks that focus on limited sustainability issues or dimensions can fail to capture the interlinkages of the integrated system and thus will provide no/limited coverage of any wider risks and benefits of projects [101]. This has implications for current legislation and regulations that frame bioenergy sustainability, where the focus is to ensure minimum benchmark performances in key themes - whole system emissions and protection of land carbon stocks and ecosystems [9]. This research suggests that this rigid approach of assessing sustainability may be incompatible with bioenergy given the dynamics of system boundaries and broad potential characteristics of bioenergy projects. There are many sustainability issues such as 'water use & efficiency', 'infrastructure requirements' and 'techno-economics' that are consistently identified as a sustainability risks but gain no coverage by legislation.

There are also no current mechanisms to ensure that potential benefits are achieved or maximised. It may not be possible to have a perfect system from the outset, but it is important that policy and decision makers have pragmatic approach that is able to improve, respond and adapt to changing circumstances [102]. This research demonstrates that by mapping sustainability of the whole system, decisions can be better informed. An approach of awarding 'credit' across a broader range of sustainability indicators in addition to requiring minimum benchmark performance in key areas, may be a better way of assessing and regulating bioenergy sustainability.

4.3.3. Should climate change mitigation be the primary sustainability criteria for bioenergy?

The principal policy driver for pursuing bioenergy results from: its ability to provide a low carbon energy source with the added attractive potential for net negative emissions; its flexibility notably as a dispatchable source of energy and as a drop-in replacement within some hard to decarbonise sectors, and; the contribution that it can make as part of a wider bioeconomy. Organisations such as the UK's Committee on Climate Change (CCC) stating bioenergy should be prioritised to generate the 'most valuable end-uses' and 'where GHG abatement can be maximised across economies' [103]. The assessments presented in this research find that there is the potential for a substantially broader set of benefits to be gained across the economy, society and the environment, indicating that the debate around bioenergy should be broadened to consider these considerations when designing policy.

There is evidence that this argument is gaining traction, for example the 2021 UK Government Policy Statement [89], committed to developing a flexible framework "under which the right biomass decarbonisation pathways can be developed and supported across the economy" that includes key wider objectives for bioenergy including 'protection of the natural environment', 'maximising circular economy benefits' and 'consideration of the role of biomass in 'hard to abate' sectors'. Realising these objectives will require 'buy-in' across Government Departments, agencies and stakeholder groups and integration of biomass and bioenergy beyond energy and decarbonisation strategies.

5. Conclusions

The Bioeconomy Sustainability Indicator Model (BSIM) was applied to map the sustainability of 16 bioenergy case studies. Our research shows how common trends in sustainability performance across projects can be identified to inform bioenergy policy and decision making. Although the research confirms the notion of 'bioenergy sustainability' being a dynamic construct rather than set destination, the varying characteristics of projects result in unique trade-offs and balances in a given scheme's sustainability performance. Flexible frameworks to map bioenergy sustainability and address sustainability risks are therefore needed. Our analysis indicates that assessment of bioenergy sustainability must increasingly broaden in scope beyond emissions and environmental considerations that are often the focus of policy frameworks - bioenergy projects can also provide potential for benefits far beyond emissions. Assuming a project delivers emissions reductions, there is an argument that projects should also be supported/promoted and replicated based on the ecosystem services and/or economic stimulation they may deliver. A more holistic approach to sustainability would also support the delivery towards the UN Sustainable Development Goals, beyond SDG7 (Affordable & Clean Energy) and SDG13 (Climate Action).

The research highlights that many of the sustainability uncertainties that have historically overshadowed bioenergy projects have been reduced through a growing foundation of research and knowledge, thus the focus of bioenergy sustainability assessments should potentially evolve to ensure that current leading risks continue to be mitigated and benefits are maximised. Thus, a rigid approach of assessing sustainability may be incompatible with bioenergy given the dynamics of system boundaries and broad potential characteristics of bioenergy projects. This research suggests policy and decision makers should have pragmatic approach to assessing sustainability that is able to improve, respond and adapt to changing circumstances. An approach of awarding 'credit' across a broader range of sustainability indicators in addition to requiring minimum benchmark performance in key areas, may be a better way of assessing and regulating bioenergy sustainability. Such an approach should be focused on facilitating innovation and interventions that enable a just and fair transition to net zero in the coming decades and beyond 2050.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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