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Mapping the sustainability of bioenergy to maximise benefits, mitigate risks and drive progress toward the Sustainable Development Goals

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ABSTRACT

Demand for biomass resources will continue to grow as bioenergy is increasingly targeted within energy strategies. Sustainability is a primary issue for large scale bioenergy, with potential to generate both risks and benefits for people, development, natural systems and for climate change – this balance of risks and benefits determining overall sustainability performance. A new sustainability mapping framework is introduced that provides a flexible tool (BSIM) to map the performances of biomass resources, supply chains, technologies and/or whole value chains against 126 indicators of sustainability. Sustainability maps are developed and assessments undertaken for case studies in the UK and Colombia. This research finds sustainability of bioenergy covers far more issues than those targeted within legislation – where land, carbon and biodiversity are prioritised. Mapping sustainability is a valuable tool to identify the leading risks and benefits to enable targeted actions to mitigate risks and to maximise and promote benefits. Mapping sustainability at different resolutions and analysing the trade-offs enables greater rationalisation of potential risks through also identifying the potential broader benefits gained. Bioenergy is intrinsically linked to the SDGs more so than other renewable technologies and should be used as a mechanism to drive sustainable development.

1. Introduction

Modern bioenergy from sustainable resources has gained a central role in providing low carbon energy to meet climate change targets in the strategies of many countries [1]. The high flexibility and potential for integration into wide ranging energy systems makes bioenergy an attractive energy option for countries at all development stages [2]. There is a rapidly growing body of research that highlights bioenergy as one of the most effective means for reducing dependencies on fossil fuels and reducing the emissions footprint from energy [3]. A direct relationship is also frequently highlighted between economic growth, urbanisation and environmental deterioration, however this impact has been found to be moderated where development aligns with transition towards modern bioenergy [4]. Although there are also consistent research findings and claims highlighting the risks associated with large scale bioenergy, focusing on issues such as competition for land and resources [5], impacts on the food sector [6] and pressures on ecosystems [7].

As bioenergy is increasingly included within energy strategies the scale of biomass resources required to balance future fuel demands will also increase. Risk of detrimental sustainability impacts linked to bioenergy may grow as the scale of resource production/collection/harvesting/mobilisation increases. These risks may be intensified further as some of the regions with the greatest biomass demands have comparatively low resource availability, and trends towards longer more complex international supply chains can already be observed [8]. These sustainability risks have the potential to be exasperated by the growing distances between the resources and supply chains, and the feedstock purchasers and bioenergy plant operators [9].

Abbreviations: BSIM, Bioeconomy Sustainability Indicator Model.

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In response there has been increasing scrutiny directed at bioenergy, calling out environmental infractions and questioning wider sustainability. To set standards and to minimise the potential sustainability risks, a wide range of institutional and regulatory instruments have been developed over the last two decades by Governments, international organisations, and independent certification companies. These range from legally binding regulations to voluntary standards where stakeholders are required to demonstrate and follow due diligence to reduce potential negative impacts [10]. Bioenergy has also gained increasing research focus to test, verify, and improve environmental and sustainable performances. Between 2000 and 2018 the number of research papers published annually focusing on biomass resources and bioenergy increased by 1545% (172 papers in 2000, 2657 in 2018), and by 2018 75% of paper included a focus on at least one bioenergy sustainability issue such as efficiencies, emissions, land, ecosystems etc [11].

Compared to other renewables, sustainability for bioenergy is a particularly crucial issue as the feedstocks fuelling bioenergy technologies will be sourced from the land, industries and existing processes that will be closely linked with multiple sectors and economic activities. Bioenergy is intrinsically linked to and influenced by natural systems, engineering, integrated supply chains and people - the balance of benefits and impacts to each of these determining the overall sustainability performance of a bioenergy system [12]. It is therefore important to fully understand all the sustainability issues relevant to a bioenergy project, to gauge where the trade-offs and challenges are and to identify which issues are most important in determining overall sustainability.

This Paper introduces a new sustainability mapping framework for bioeconomy projects as developed by the UK Supergen Bioenergy Hub [13]. The 'Bioeconomy Sustainability Indicator Model' (BSIM) is designed to provide a flexible tool to map the performances of biomass resources, supply chains, technologies and/or whole value chains against over 120 indicators of sustainability. The paper presents sustainability maps for 3 UK biomass resource case studies and 2 bioenergy value chain case studies from Colombia. Through analyses of the case study results, this research aims to highlight the value gained through mapping the complete sustainability performances of projects – identifying areas of risk and benefit and highlighting a project's potential influence on the United Nation's Sustainable Development Goals (SDGs).

2. Sustainability & Bioenergy

The sustainability risks of bioenergy are not a new challenge. As long ago as 1713 German Mining Director Hans Carl von Carlowitz reacted to deforestation across Europe, resulting from clearage for agriculture and use of wood to fuel development – arguing for letting the trees grow to maturity and for replanting new trees after harvesting, thus conserving the forest resource and production capacity [14]. Sustainability issues linked to expanding demand for biomass resources for energy continue and have evolved as priorities change. Modern examples include social conflicts and environmental impacts resulting from production of first generation biofuels on lands that would otherwise be used for food [15], also deforestation and land-use change impacts linked to the establishment of energy crop plantations [16].

As the sustainability of bioenergy debate continues to develop, organisations have worked to update regulations for improving sustainability as different issues rise in prominence [17]. An indication of current priorities may be highlighted by the output of the consultation carried by the European Commission when updating the 2018 Renewable Energy Directive [18]. Following engagement with both expert stakeholders and the public, the primary sustainability risks for bioenergy were identifies as: i) biogenic CO_2 and supply chain emissions, ii) impacts on biodiversity, soil and air quality, iii) efficiency of installations, and iv) administrative burden costs [19]. It is important that bioenergy sustainability assessment schemes and as far as possible legislation provide coverage of these primary issues, but should also provide coverage of wider sustainability issues and have the flexibility to capture the rise in prominence of new issues and those relevant to different projects and timescales [20].

2.1. Sustainability governance framework

A range of methods and approaches have been developed to regulate, assess and monitor bioenergy sustainability performances [14]. These may be grouped as: i) Government Regulations, designed to enforce minimum performance standards for bioenergy projects, and; ii) Certification Schemes developed for organisations to voluntarily assess and regulate the sustainability performance of their project. Each of these are described below through discussion of prominent schemes.

2.1.1. Government sustainability regulations – focus on the RED

Across much of Europe the targets and commitments of the European Union's (EU) 2009 Renewable Energy Directive (RED) [21] (and the 2018 update [18]) have provided the policy framework designed to stimulate sustainable growth of renewables in reflection of Europe's climate change targets. In practice the RED is implemented either through national regulation or through approved voluntary sustainability standards built on the EU RED's sustainability standards. The EU RED's sustainability criteria for 'plant-derived fuels (biofuels)' are summarised within Table 1.

Driven by Europe's renewable energy and climate change targets, Europe has large and growing demands for bioenergy - Europe is the leading global importer of wood pellets, wood chips and particles, and second largest importer of biodiesel, bioethanol and biomethane fuels and related commodities [22]. To count towards EU national renewable energy targets all consumed biofuels must comply with EU RED sustainability criteria. As a consequence all feedstocks and commodities sourced by European countries from the international trade markets are assessed against the EU RED's sustainability criteria – the criteria are therefore used by many organisations and stakeholder far beyond the borders of the EU [23].

2.1.2. Voluntary bioenergy sustainability certification schemes

Voluntary sustainability certification schemes are a key mechanism for increasing and verifying bioenergy sustainability worldwide. Verification being the vital step to assure that the defined sustainability performances are fulfilled [24]. Many of the voluntary schemes are directly linked to the EU RED and are intentionally designed to provide assessment against the EU RED's sustainability criteria, so accredited producers/feedstocks gain automatic approval for EU buyers. Voluntary schemes vary in scale and scope, and can be broadly categorised as either: Full Bioenergy Schemes that provide assessment frameworks covering complete bioenergy value chains from the resource through to its conversion to bioenergy or a bio-product, or; Sector Focused Schemes that are developed for a specific sector, feedstock or processes [25].

Table 2 presents a summary of the sustainability themes covered by many of the leading voluntary schemes. Each of the schemes represented provide assessments to determine eligibility against the RED II criteria and provide options for organisations to verify and certify performances. Full bioenergy schemes included are the Roundtable on Sustainable Biomaterials (RSB) that may be used to assess both bioenergy projects and that for wider

Table 1
EU renewable energy directive (RED II) sustainability criteria & verification requirements [19].

Requirements Applied for Biofuels, Bioliquids and Biomass Fuels	
Criteria	**Details**
GHG Emission Savings	✓*At least 65% for biofuels, biogas for the transport sector & produced bioliquids in operation from January 2021.* ✓*At least 70% for electricity, heating & cooling from biomass fuels in operation from January 2021 until December 2025.80% from January 2026.*
Wastes & Residues	✓*Required to fulfil GHG emission savings* ✓*Required to address impacts on soil quality and soil organic carbon*
Land with High Biodiversity Values	✓*No production from land with high biodiversity values (including primary forest, wooded land, areas with designated protection, areas of high biodiversity).*
Land with High Carbon Stock Values	✓*No production from land with high carbon stocks (including wetlands, continuously forested land, peatland, >1 ha land with trees higher than 5 m and a canopy cover of between 10% and 30%, or land with trees able to reach those thresholds in situ*
Minimising Risk of Unsustainable Production	✓*Appliance of national and/or sub-national laws (for harvesting, monitoring, enforcement systems of forest biomass)* ✓*Alternatively seek similar risk mitigation/management systems.*
Verification	✓*Provide evidence ensuring carbon stocks and sink levels are maintained, or strengthened over the long term.* ✓*Alternatively seek management systems to manage.*
Mass Balance	✓*Detailed criteria characterising if consignments of raw material or biofuel with different sustainability characteristics can be mixed*

Table 2
Coverage of sustainability themes within leading voluntary certification schemes.

Coverage of Sustainability Themes	RED	Voluntary Certification Schemes								
		Full Bioenergy Assessment Schemes & Frameworks				Sector Focused Schemes				
		RSB	ISCC	Better Biomass	ISO 13065	SBP	CORSIA	RTRS	RSPO	Bonsucro
Health			✓	✓	✓	✓		✓	✓	✓
Livelihoods		✓	✓		✓	✓	○	✓	✓	✓
Society		✓			✓	✓	○	✓	✓	✓
Economy			✓		✓	✓		✓	✓	✓
Infrastructure						✓			✓	
Feedstocks		✓			✓	✓				
Technologies		✓			✓	✓				
Energy Sector		✓								
Bioeconomy		✓								
Land Strategy	✓			✓	✓	✓		✓	✓	✓
Land & Ecosystems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Air Quality		✓	✓		✓	✓	○			
Water Systems		✓	✓	✓	✓	✓	○	✓	✓	✓
Climate Governance		✓			✓	✓		✓	✓	✓
Carbon & Emissions	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Replacing Fossil Fuels				✓		✓	✓			
Key:	✓	Coverage of sustainable theme within certification scheme.								
	○	Planned future coverage of sustainability theme within certification scheme.								

biomaterials [26]; the International Sustainability and Carbon Certification (ISCC) scheme that may be used to assess both bioenergy projects and those from wider sectors [27]; the Better Biomass scheme that allows assessment of biomass and other bio-based products [28], and the; International Organization for Standardization's 'Sustainability Criteria for Bioenergy' (ISO 13065:2015) that focuses on whole supply chains of bioenergy projects [29]. Sector focused schemes included in Table 2 are the: Sustainable Biomass Program (SBP) for woody biomass feedstocks [30]; the Bonsucro scheme that has been developed to focus on the sugarcane sector [31]; the Roundtable on Sustainable Palm Oil (RSPO) scheme for the palm sector [32]; the Roundtable on Responsible Soy Association (RTRS) scheme for the soy sector [33], and; the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) developed specifically for alternative fuels for aviation [34].

2.1.3. Criticisms of bioenergy sustainability regulations & certification schemes

Despite the large influence of sustainability regulations such as the EU RED II, the scope of sustainability issues included in the legislation are extremely limited. Focus keenly placed on climate change and land themes – ensuring favourable energy emissions compared to fossil fuels and maintenance of land carbon stocks and ecosystem biodiversity. Although these are each vital, Table 2 clearly highlights some of the many sustainability issues that do not gain legal coverage. None of the schemes reviewed in this paper provide a framework that potentially covers all the sustainability themes listed in Table 2.

There is further argument that in reality a bioenergy project will likely be shaped by local and regional peculiarities in addition to the perceptions and differing priorities of local and regional stakeholders – each bioenergy project being bespoke and therefore unsuitable for assessment within rigid sustainability frameworks that maybe incapable of capturing the project [3]. Accreditation schemes provide an assessment of whether threshold performances are achieved, they do not offer analyses of the many sustainability nuances and trade-offs relevant for most bioenergy projects. Sustainability frameworks also largely aim to assess and benchmark performances of planned or operational projects, they do not provide mechanisms to inform choices. An assessment of both the balance and trade-offs of risks and benefits would allow more informed decisions about different biomass resources, technologies and vector configurations [35].

3. Methodology – Developing a tool to map the sustainability of Bioenergy

A model was developed to provide a flexible tool to map the sustainability of biomass resources, supply chains, technologies, and/or whole bioenergy value chains. Fig. 1 provides a schematic of the overall approach of the 'Bioeconomy Sustainability Indicator Model' (BSIM) illustrating the architecture:

(1) The model was developed around the concept that there will be both sustainability risks and benefits attributed to each life cycle step within any bioeconomy project value chains, and sustainability can be mapped to identify and analyse these risks and benefits.
(2) A comprehensive list of sustainability issues was identified covering each life cycle stage of bioenergy value chains.
(3) These issues are structured within a sustainability assessment framework following a hierarchy of: broad sustainability categories (e.g. climate change), sustainability themes (e.g. emissions), sustainability indicators (e.g. land use change) and individual sustainability issues (e.g. direct land use change). The BSIM is calibrated through selecting the sustainability issues relevant to a project and identifying the potential occurrence of a sustainability risk and/or benefit by scoring the level of impact from very low to very high. Additionally, each sustainability issue has a weighting value to account for the greater or lesser potential influence within the whole system compared to all other issues considered.
(4) The BSIM generates outputs mapping the key sustainability risks and benefits, and calculates an overall sustainability score for the project based on the individual indicator scores and weightings. Sustainability scores for a given project provide an index value to allow comparison between projects.
(5) The BSIM is also designed to map the potential influence a bioenergy project may have on the United Nation's Sustainable Development Goals (SDGs).

The BSIM is designed with flexibility to all allow potential application to any bioeconomy project or any specific element within a wider scheme. The BSIM provides a fixed calculation framework where through varying the choice of issues selected and updating weighting values, can be used to map the sustainability of projects in different countries or bespoke regions of interest. The BSIM is an open access tool that can be found online [36] and is supported by the BSIM Guidance Manual [37].

3.1. Stakeholder engagement to inform model development

The BSIM was developed by the UK Supergen Bioenergy Hub [13] through active engagement with bioenergy stakeholders, who have experience working on both UK and international bioenergy and bioeconomy projects. During a series of workshops, stakeholders from academia, industry and policy discussed and informed the BSIM's overarching concepts, the list of sustainability issues considered, the sustainability assessment framework, the calculation mechanics, the weightings of sustainability issues, and who also tested the BSIM through mapping of bioenergy case studies. Engagement was facilitated through individual discussions with specialists, through five 'Bioenergy Sustainability Expert Workshops', through dedicated sessions at Supergen's Researchers Day 2021 and with the Supergen Core Management Group and Advisory Groups. To test the application of the BSIM to different regions, the authors worked with a Bioenergy Expert from Colombia to develop regional case studies. Further details of the engagement activities undertaken and the stakeholders who contributed are listed in the Supplementary Materials.

3.2. Developing a bioenergy sustainability assessment framework

The choice of sustainability issues included within the BSIM was influenced by the large body of existing work that has focused on bioenergy, the bioeconomy and related sustainability assessment schemes. Key sources used included the EU RED II criteria [18], Global Bioenergy Partnership's sustainability indicator framework

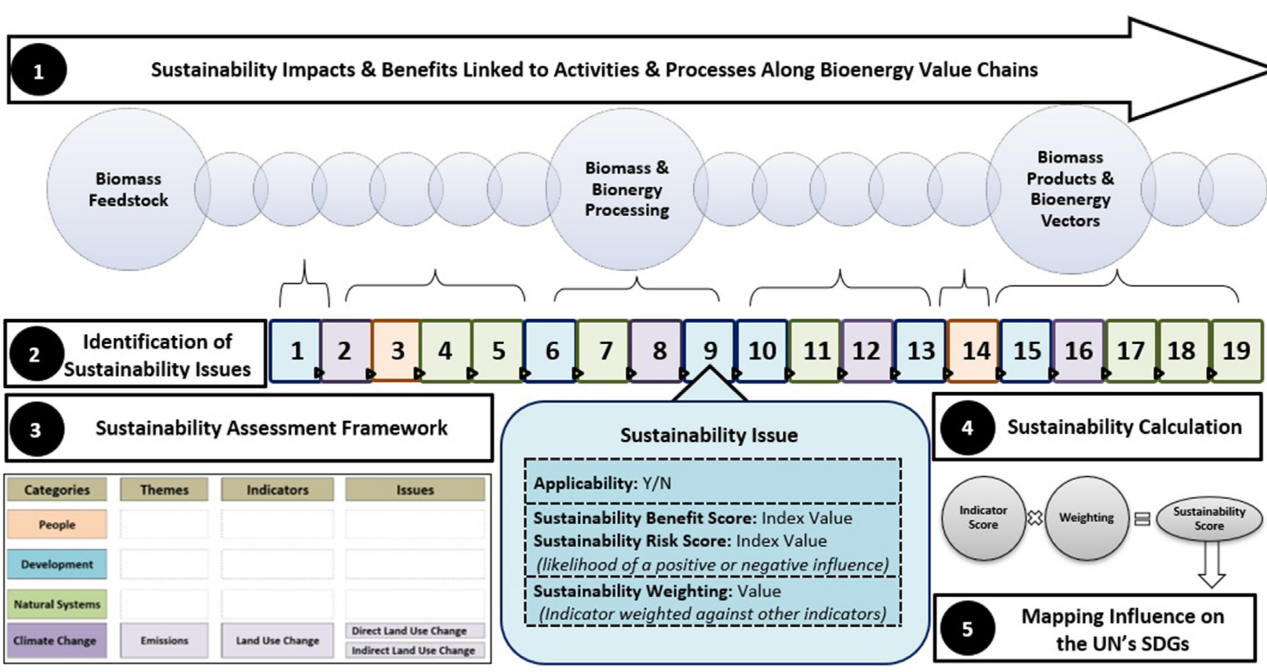

Fig. 1. Bioenergy sustainability indicator model architecture.

[38], the Roundtable on Sustainable Biomaterials assessment criteria [26] and the many individual targets that make up the United Nation's Sustainable Development Goals [39]. The final choice of issues included within the BSIM and the structuring of a sustainability assessment framework was developed through the stakeholder engagement activities.

The resulting sustainability assessment framework includes coverage of 126 different sustainability issues. These are structured within 38 sustainability indicators, 16 sustainability themes and 4 sustainability categories. Table 3 provides a summary of the categories, themes and indicators covered by the BSIM, and an introduction to each Sustainability Category is included below. 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 [37].

3.2.1. Bioeconomy sustainability - people

Within the People sustainability category the BSIM covers three core themes: Health, Livelihoods and Society. Influence on Health may include issues such as potential changes in mortality rate and disease burden, for example as a consequence of disease attributable to contaminants and air pollution [40]. Also influences to occupational risks and safety hazards linked to incidences of injury, illness or fatalities as a consequence of bioeconomy activities [41]. Influence on food systems, such as changes in food commodity production, supply, prices, and influences on the productivity and resilience of agriculture [42].

Bioeconomy sustainability issues related to the Livelihoods theme include potential influences on land management, ownership and access [43], working conditions [44], jobs and changes in income [45].

The Society theme is developed to map the potential influence on wider society including on issues of diversity and equality, on institutions and legal systems, and its influence through partnerships with community groups [46], with industry and government organisations [47]. Changes in energy access as consequence of bioeconomy projects is a further crucial societal issue that may provide wider sustainability influences for both households and industry [48].

3.2.2. Bioeconomy sustainability - development

The Development sustainability category covers seven themes. This includes mapping potential bioeconomy project's influences on the Economy and Infrastructure. For example, potential risks or benefits for GDP, trade and the economic performance of wider sectors, and the broader influences of increasing renewable energy generation albeit at the cost of required economic support mechanisms [8,49]. Also the potential risks and benefits resulting from use of existing and new infrastructure [50]. The production, mobilisation or harvesting of Feedstocks may also generate both risks and benefits resulting from varying production methods and wider strategies that may change the productivity of land and

Table 3
Sustainability indicator assessment framework.

Sustainability 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 Characteristics*
Natural Systems	Land	*Soil*
		Ecosystems
	Air	*PM Pollutants*
		Oxide Pollutants
		Heavy Metal
	Water	*Water Use & Efficiency*
		Water Quality
		Water Systems
Climate Change	Governance	*Climate Action*
		Standards
	Carbon & Emissions	*Whole Life Cycle Emissions*
		Land & Carbon Stocks
		Counterfactual Considerations
	Energy System	*Replaced Fuels*

processes [51]. Factors such as the spatial distribution of and competition for feedstocks potential may have widespread sustainability implications [52,53].

Bioeconomy projects may also develop new Technologies and intellectual property that may have sustainability implications such as improving efficiencies or economic performances. Increased bioeconomy activities such as bioenergy will also likely have sustainability implications for the broader Energy Sector [54], specifically for the Bioeconomy [55] and for Land Utilisation [56].

3.2.3. Bioeconomy sustainability - natural systems

The Natural Systems sustainability category covers three broad themes: Land, Air and Water. Bioeconomy projects may have direct influences on the Land, such to the health and productivity of soils [57], to ecosystems and biodiversity [58,59] and they may also change land uses and classifications [60]. Potential influences on the Air include changes in pollutants [61] and particulate emissions [62]; and influences to Water include changes in heavy metal pollutants [63,64] use of fertilisers and pesticides [65], use of water resource that may have impact on water availability [66], flooding [67] and water stresses [68].

3.2.4. Bioeconomy sustainability - climate change

The Climate Change sustainability category covers three themes: Governance, Carbon and Emissions and Energy System. Bioeconomy project's have the potential to influence climate change Governance as may directly contribute to achieving climate change and sustainability targets, legislation and regulations [49], also potentially raising awareness to climate change issues [69]. Standards are important for driving the effectiveness of projects in their ability to deliver low carbon sustainable energy [10].

Carbon and Emissions represents a key environmental issue for any bioeconomy project. In the case of bioenergy projects there is potential for the storage or release emissions at each life cycle stage of a given value chain, including from the production/mobilisation/harvesting of feedstocks, resource transportation, processing and pre-treatment activities and the conversion of feedstocks [35]. Biomass production strategies may have large implications for land and carbon stocks as can drive large fluxes of carbon between the atmosphere and terrestrial carbon sinks. It is important to also account counterfactual considerations that describe what may otherwise have happened. For example if waste materials are used for bioenergy that would otherwise be managed through a potentially high environmental impact pathway such as being sent to landfill, using the wastes for bioenergy could result in the mitigation of large environmental impacts associated with landfilling [70].

Projects can also influence the sustainability of broader Energy Systems, for example bioenergy will be beneficial where it replaces fuels with higher GHG intensities. Bioenergy schemes that substitute use of fossil fuels or traditional bioenergy technologies may also generate broader sustainability benefits beyond reduced emissions [48].

3.3. BSIM modelling mechanics

The BSIM is designed to calculate a series of ‘sustainability performance scores’ (SPS) at each level of the sustainability assessment framework – a score for each issue, indicator, theme, category and an overall score for the project. This allows the mapping of the sustainability performances between different aspects of a project, identifying issues, indicators, themes or categories where there may be a risk or benefit to sustainability and mapping the trade-off within the system. Additionally, this allows a harmonised comparison and benchmarking of performances across projects where more than one project is assessed.

The SPS scores are index values that are calculated as a function of the issue scores (IS)[1] and the issue weighting (IW)[2] for each sustainability issue within the BSIM (Equation 1). This ‘likelihood x magnitude’ approach is the standard method for quantitating risk assessment in science, and ensures that risks of catastrophic impact or high benefit are not neglected or dismissed due to low probability [14].

3.3.1. Issues scores (IS)

The user calibrates the BSIM to develop bespoke issues scores (IS) to reflect the project modelled. Users are required to assign two ‘Likelihood Index’ (LI)[3] scores for each sustainability issue, to reflect the likelihood that a sustainability risk or benefit will occur as a consequence of the project.

The LI score options are: ‘none’ (index score 0), ‘very low’ (score 1), ‘low’ (score 2), ‘medium’ (score 3), ‘high’ (score 4), ‘very high’ (score 5). Users also have the option to apply a ‘boost index’ (BI)[4] to these scores where the user believes a given sustainability issue is particularly relevant or irrelevant to the project – options ‘low’ (multiplier 1), ‘standard’ (multiplier 2) and ‘high’ (multiplier 3). The IS scores are calculated as a function of the likelihood score and the multiplier (Equation 2). For example, a project's IS risk score for a prominent sustainability issue assigned with a ‘high’ likelihood for generating a risk (score 4) with an addition ‘high’ boost (multiplier 3) would be 12.

There is also the alternative option for users to insert bespoke IS values if preferred, although when comparing the sustainability performance across projects it is important to ensure a standard approach is followed.

3.3.2. Issue weightings (IW)

Weighting are used within the BSIM to take account of the varying influence of different sustainability issues, each potentially having greater or lesser importance in determining overall sustainability. For example GHG emission performances are a fundamental factor influencing the overall sustainability performance of a given project [70].

The method for calculating weightings within the BSIM draws influence from comparable assessment schemes, including industry sustainability assessment schemes [26], broad environmental impact assessment schemes [71] and existing bioenergy assessment methods [72]. The BSIM can be calibrated to either use default issue weightings or have custom issue weightings to be decided by the BSIM user. The default weightings were informed by the research's stakeholder engagement exercises (Section 3.1). Stakeholders compared and discussed sustainability performance considerations for a large number of biomass feedstocks,

[1] Issue Scores (IS) - Two scores attributed to each sustainability issue, determining the potential sustainability benefit (IS^b) and sustainability risk (IS^r). These values are calculated within the BSIM as a function of the LI and BI scores.

[2] Issue Weighting (IW) – Two scores attributed to each sustainability issue, determining the influence of each issue on overall sustainability compared to the comparative influence of all sustainability issues within the BSIM. Default values for the sustainability benefit issue weighting (IW^b) and sustainability risk issue weighting (IW^r) are built into the BSIM as informed by stakeholder engagement. Although the BSIM user can also opt to use custom IW values.

[3] Likelihood Index (LI) - Two scores attributed to each sustainability issue, determining the perceived likelihood that there will be a sustainability benefit (LI^b) and/or sustainability risk (LI^r) as a consequence of the project. These values are determined by the BSIM user to reflect the bioenergy project being modelled.

[4] Boost Index (BI) - Two additional scores that the BSIM user may decide to attribute to each sustainability issue, providing an increase or reduction in the sustainability benefit (BI^b) and/or sustainability risk (BI^r) based on the specific project being modelled.

conversion technologies, products and energy vectors, identifying on an index scale of 1–5 (1 very low, 2 low, 3 medium, 4 high, 5 very high) the extent that a given issue may generate a sustainability benefit and/or a sustainability risk. For example, stakeholders identified that bioenergy substituting use of fossil fuels would potentially generate a 'high to very high' sustainability benefit (averaged score 4.50) and a 'very low to low' sustainability risk (averaged score 1.5).

Although the weightings calculated for each sustainability issue can be changed within BSIM, these should remain fixed when undertaking studies to compare sustainability performances across different projects. A complete list of the calculated default BSIM issue weightings are included in the BSIM Guidance Manual [37].

Equation 1: Calculating the Sustainability Performance Scores (SPS) within the BSIM

$$
\begin{aligned}
&i) \quad SPS^{b} = IS^{b} \times IW^{b} \\
&ii) \quad SPS^{r} = IS^{r} \times IW^{r} \\
&iii) \quad SPS^{issue} = \frac{SPS^{b} + SPS^{r}}{2} \\
&iv) \quad SPS^{indicator} = Mean\ [SPS^{issue}]^{n} \\
&v) \quad SPS^{theme} = Mean\ [SPS^{indicator}]^{n} \\
&vi) \quad SPS^{category} = Mean\ [SPS^{theme}]^{n} \\
&vii) \quad SPS^{overall} = Mean\ [SPS^{category}]^{n}
\end{aligned}
\tag{1}
$$

Equation 2: Calculating the Sustainability Issue Scores (IS) within the BSIM

$$
\begin{aligned}
&i) \quad IS^{b} = LI^{b}\ x\ BI^{b} \\
&ii) \quad IS^{r} = LI^{r}\ x\ BI^{r}
\end{aligned}
\tag{2}
$$

Where:

IS^b – Issue Score, sustainability benefit value determined by the BSIM user when modelling a project.

IS^r – Issue Score, sustainability risk value determined by the BSIM user when modelling a project.

IW^b – Issue Weighting, sustainability benefit weighting. Either default value within BSIM or a user custom value.

IW^r – Issue Weighting, sustainability risk weighting. Either default value within BSIM or a user custom value.

SPS^b – Sustainability Performance Score, calculated benefit for each sustainability issue within the BSIM.

SPS^r – Sustainability Performance Score, calculated risk for each sustainability issue within the BSIM.

SPS^{issue} – Sustainability Performance Score, calculated for each sustainability issue within the BSIM.

$SPS^{indicator}$ – Sustainability Performance Score, calculated for each sustainability indicator within the BSIM.

SPS^{theme} – Sustainability Performance Score, calculated for each sustainability theme within the BSIM.

$SPS^{category}$ – Sustainability Performance Score, calculated for each sustainability category within the BSIM.

SPS overall – Sustainability Performance Score, calculated for the overall project.

LI^b – Likelihood Index, value selected by the BSIM user to determine likelihood of a sustainability benefit.

LI^r – Likelihood Index, value selected by the BSIM user to determine likelihood of a sustainability risk.

BI^b – Boost Index, optional benefit amplification value selected by the BSIM user to increase/decrease importance of sustainability issue for the project.

BI^r – Boost Index, optional risk amplification value selected by the BSIM user to increase/decrease importance of sustainability issue for the project.

3.4. Mapping the links between bioeconomy projects & the UN SDGs

The BSIM has also been developed to provide an assessment of how bioeconomy projects may influence the UN's Sustainable Development Goals (SDG). Each of the 17 SDGs are built on a number of separate targets (listed in BSIM Guidance Manual [37]) that characterise broad ranging sustainability issues. Through stakeholder engagement activities during the model development process, potential links were identified between each of the BSIM's 126 sustainability issues and the individual targets of the SDGs.

Fig. 2 provides an overview of the breadth of potential links between the sustainability of bioeconomy projects and the SDGs – shown to have the potential to influence every SDG. The n-values within Fig. 2 denote the number of linkages identified between the many sustainability issues that make up each of the BSIM's themes and the targets of each SDG. However, as the SDGs are also intrinsically linked and influence each other, the true potential influence of projects on the SDGs may be significantly larger than highlighted within Fig. 2. Where the sustainability risks of projects are mitigated and the benefits maximised, bioeconomy projects such as bioenergy schemes may provide a valuable mechanism for countries to drive their progress towards sustainable development.

4. BSIM demonstration - Bioenergy case studies

The BSIM is applied to analyse two bioenergy case studies, designed to demonstrate how the model can be used to map the sustainability of bioenergy projects, how different bioenergy projects can be compared, but also to highlight the potential role bioenergy may have in providing wider sustainability for people, development, natural systems and the climate.

4.1. Case study 1: mapping the sustainability of UK biomass resources

The UK is targeting bioenergy to provide a leading role in the future renewable energy, decarbonisation strategy and as part of the growing UK bioeconomy [55]. Key biomass resources targeted to balance the UK's future biomass demands include energy crops, agri-residues and municipal solid wastes (MSW). The BSIM was calibrated using the outputs from a dedicated activity as part of the research's stakeholder engagement workshops, with the aim of mapping the sustainability of these three biomass resource categories. The stakeholders were tasked with analysing the sustainability of the UK biomass resources, focusing explicitly on their mobilisation (production/harvesting/sourcing) as potential bioenergy feedstocks. Stakeholders did not consider the downstream uses of these feedstocks. The stakeholders informed BSIM calibration settings for the three UK case studies, these are presented in the Supplementary Materials. For the UK case studies the BSIM's default weightings were applied, reflecting the values developed through the stakeholder engagement activities. The default weightings are presented in the Supplementary Materials and the BSIM Guidance Manual [37].

4.2. Case study 2: mapping the sustainability of bioenergy from agri-residues in Colombia

Bioenergy is a leading alternative energy option for countries all around the world aiming to decarbonise, whilst providing the energy required to drive sustainable development [48]. Colombia is a

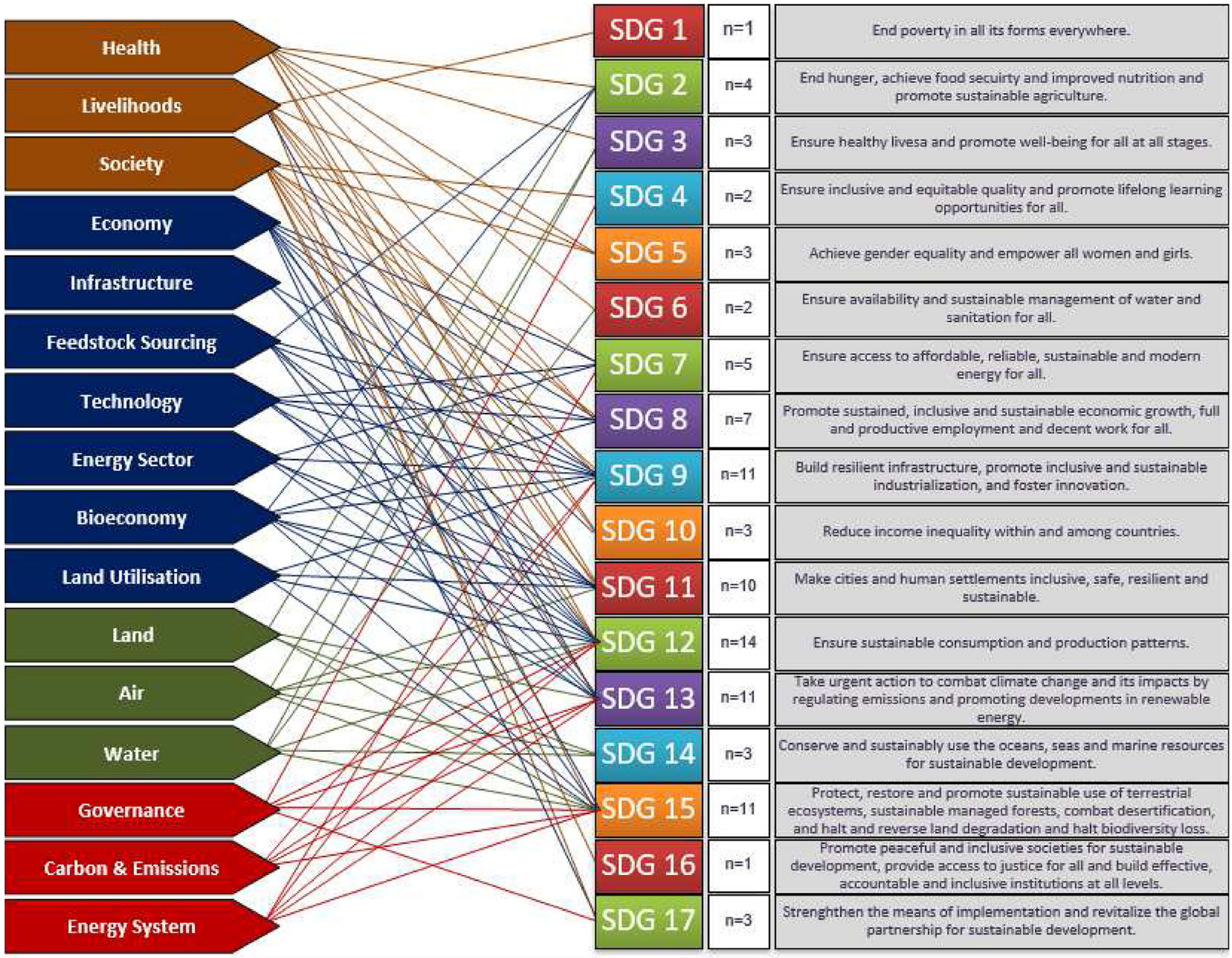

Fig. 2. Linkages between the BSIM sustainability assessment framework & the SDGs.

country with large potential bioenergy opportunities linked to the agriculture sector [25]. Agri-residues from agricultural processes such as coffee production represent key opportunities for the bioenergy sector.

The BSIM was applied to assess a case study of a full bioenergy value chain – using coffee stem residues in Colombia to provide feedstock for electricity generation. This case study was selected to undertake a full sustainability appraisal to complement previous techno-economic and GHG lifecycle assessments [73] and bioenergy process modelling studies [74] for the same project. This case study providing an opportunity to map sustainability of a bioenergy project developed specifically to drive sustainable development.

The BSIM was calibrated to model two case study scenarios: i) generation of electricity from coffee stem residues, replacing existing grid electricity, and ii) generation of electricity from coffee stem residues, replacing electricity from diesel generators. The BSIM was calibrated to analyse the Colombia case studies through consultation with a Colombian Bioenergy Expert whose research inspired the case studies. The Colombia Case Study BSIM calibration settings are presented in the Supplementary Materials.

5. Results

The results section aims to demonstrate the functionality of the BSIM and highlight the value of mapping the sustainability of projects through analysing the outputs from the two described case studies. Presented results show how the BSIM may be applied to map the sustainability performance of individual projects and highlight the many trade-offs of potential risks and benefits that may be generated - allowing comparison of sustainability performances between projects.

5.1. Sustainability performance of UK biomass resources

The radar graphs presented in Fig. 3 map outputs from the BSIM at the sustainability indicator level, presenting index values that reflect the balance of potential sustainability risks and benefits. The radar graphs are shaded to delineate the different sustainability categories of the BSIM. Fig. 3 is supported by the data presented in Tables 4–6, where overall sustainability performance scores are presented at the Category, Theme and Indicator resolutions. The shading within the Tables highlights where there is likelihood of an

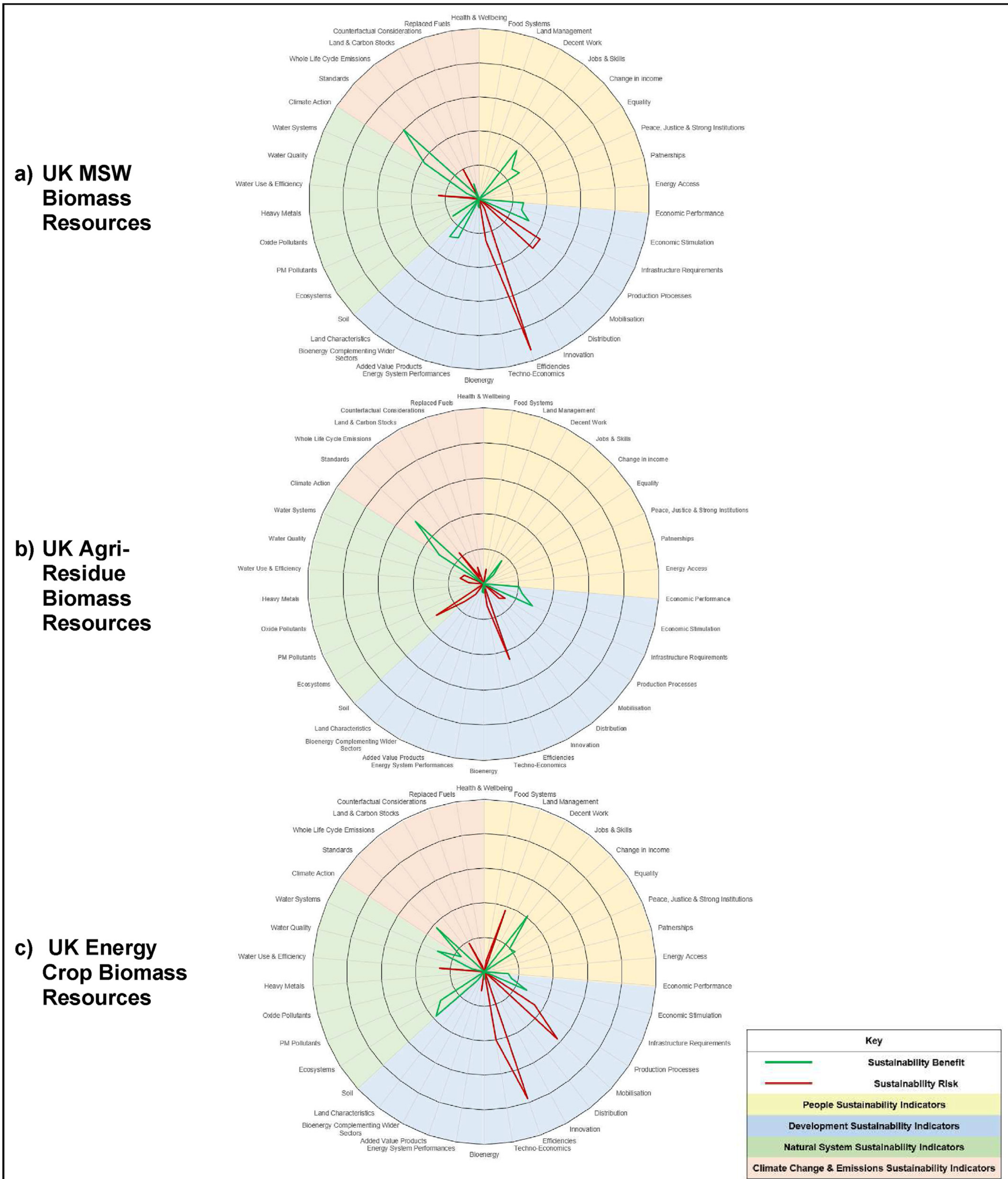

Fig. 3. Sustainability Mapping, assessment of the balance of potential sustainability risks and benefits of sourcing UK biomass resources as feedstocks for bioenergy.

Table 4
Sustainability Performance Scores, sourcing UK MSW biomass resources as feedstocks for bioenergy.

Sustainability Categories Index Scores				Sustainability Theme Index Scores				Sustainability Indicator Index Scores			
	SPS^r	SPS^b	SPS		SPS^r	SPS^b	SPS		SPS^r	SPS^b	SPS
People	-2.5	4.2	0.9	Health	-	-	-	Health & Wellbeing	-	-	-
								Food Systems	-	-	-
				Livelihoods	-3.8	5.2	0.7	Land Management	-	-	-
								Decent Work	-	-	-
								Jobs & Skills	-5.7	10.5	2.4
								Change in income	-6.6	10.3	1.9
				Society	-1.1	1.9	0.4	Equality	-4.3	8.1	1.9
								Peace, Justice & Strong Institutions	-	-	-
								Partnerships	-	-	-
								Energy Access	-	-	-
Development	-12.1	16.8	2.4	Economy	-5.7	9.0	1.6	Economic Performance	-8.1	12.1	2.0
								Economic Stimulation	-3.1	5.3	1.1
				Infrastructure	-9.2	14.1	2.5	Infrastructure Requirements	-8.5	13.2	2.4
				Feedstocks	-7.0	3.7	-1.6	Production Processes	-7.1	2.5	-2.3
								Mobilisation	-12.1	8.2	-2.0
								Distribution	-	-	-
				Technology	-10.6	6.1	-2.2	Innovation	-5.2	4.9	-0.2
								Efficiencies	-14.1	4.1	-5.0
								Techno-Economics	-10.3	8.3	-1.0
				Energy Sector	-3.3	4.2	0.5	Bioenergy	-1.4	2.1	0.3
								Energy System Performances	-5.0	5.9	0.5
				Bioeconomy	-3.9	5.5	0.8	Added Value Products	-	-	-
								Bioenergy Complementing Wider Sectors	-9.4	13.6	2.1
				Land Utilisation	-9.4	13.9	2.2	Land Characteristics	-8.7	13.0	2.2
Natural System	-3.3	4.7	0.7	Land	-1.9	3.5	0.8	Soil	-	-	-
								Ecosystems	-3.7	6.3	1.3
				Air	-	-	-	PM Pollutants	-	-	-
								Oxide Pollutants	-	-	-
								Heavy Metals	-	-	-
				Water	-5.5	5.3	-0.1	Water Use & Efficiency	-8.5	6.4	-1.1
								Water Quality	-4.6	4.5	0.0
								Water Systems	-2.9	3.9	0.5
Climate Change	-5.0	9.9	2.4	Governance	-5.4	12.3	3.5	Climate Action	-5.9	11.4	2.7
								Standards	-4.1	11.7	3.8
				Emissions	-5.2	5.3	0.1	Whole Life Cycle Emissions	-4.5	5.1	0.3
								Land & Carbon Stocks	-4.4	2.6	-0.9
								Counterfactual Considerations	-5.2	7.0	0.9
				Energy Systems	-	-	-	Replaced Fuels	-	-	-

overall sustainability risk (red) or benefit (green) across the sustainability map. Presentation of the full results at the Issue level are included within the Supplementary Materials.

At the category resolution, sustainability scores within Tables 4–6 show that utilisation of UK MSW, agri-residues and energy crops will provide overall net sustainability benefits for people, development, natural systems and climate change & emissions. The only exception is shown in Table 5 where use of agri-residues are highlighted as potentially posing a net sustainability risk for natural systems. Despite these overall net benefits, assessment of the outputs at a greater resolution such as presented in the radar graphs highlight there are areas of both sustainability risk and benefit for each the of UK biomass resources. Mapping sustainability at the different resolutions can highlight the many trade-offs and varying performances across issues, whilst also allowing identification of the key individual issues that contribute to determining overall sustainability performance.

Within the results there are a series of consistent issues that are shown to provide either potential risks or benefits for each category of UK biomass resource. For example, a clear benefit is identified through the potential generation of new jobs and skills that may result from the greater use of the resources for bioenergy. The development of fuel/technical/chain of custody standards is a further issue shown to consistently generate sustainability benefits. In contrast consistent potential risks are identified linked to feedstock production/mobilisation/distribution. There are particularly acute risks attributed to techno-economics and efficiencies – suggesting this is where further research should be focused in the UK.

The results for MSW presented in Graph-a of Fig. 3 and Table 4, highlight that greater use of MSW for bioenergy has the potential to provide broad economic benefits including changes in income, infrastructure and stimulation for wider economic sectors. There are also notable potential benefits for land utilisation and for ecosystems as use of MSW may reduce the levels of waste resources sent to landfill and there are not many of the land risks that can be attributed to other bioenergy feedstocks. Although risks for natural water systems are shown to be a pertinent for projects using MSW resource.

The results for agri-residues presented in Graph-b of Fig. 3 and Table 5, demonstrate that their use as bioenergy feedstocks may also provide broad economic benefits. Including potential benefits for economic performance, providing stimulation for wider economic sectors and particularly the bioeconomy, and through infrastructure. This potentially having a positive impact on jobs and skill creation and increased income. However, the results also highlight potential sustainability risks that may need to be mitigated, including potential impacts on the land such as to soil and ecosystem health that could result through over exploitation of the resource – this posing a potential risk to food systems. Further risks are identified for natural water systems with potential impact linked to water use and quality. Risks are also highlighted within the climate change and emissions category, associated with the potential emissions that may result from an unsustainable agri-residue mobilisation strategy [70].

The sustainability performance results for energy crops presented in Graph-c of Fig. 3 and Table 6 highlight a broad range of potential benefits that may be gained through their use as feedstocks. Societal and livelihood benefits such as jobs and skills and development benefits such as that provided by infrastructure are shown to be consistent with the results of the other resources. Notably greater potential benefits are shown in the natural system category where energy crops are highlighted as potentially

Table 5
Sustainability Performance Scores, sourcing UK agri-residue biomass resources as feedstocks for bioenergy.

Sustainability Categories Index Scores				Sustainability Theme Index Scores				Sustainability Indicator Index Scores			
	SPS^r	SPS^b	SPS		SPS^r	SPS^b	SPS		SPS^r	SPS^b	SPS
People	-2.2	2.4	0.1	Health	-0.5	0.1	-0.2	Health & Wellbeing	-	-	-
								Food Systems	-1.2	0.3	-0.5
				Livelihoods	-3.8	3.9	0.1	Land Management	-	-	-
								Decent Work	-	-	-
								Jobs & Skills	-5.6	8.0	1.2
								Change in income	-6.5	7.9	0.7
				Society	-	-	-	Equality	-	-	-
								Peace, Justice & Strong Institutions	-	-	-
								Partnerships	-	-	-
								Energy Access	-	-	-
Development	-9.5	13.0	1.8	Economy	-5.0	7.6	1.3	Economic Performance	-6.2	9.3	1.6
								Economic Stimulation	-3.3	5.3	1.0
				Infrastructure	-8.6	13.3	2.3	Infrastructure Requirements	-8.0	12.4	2.2
				Feedstocks	-4.5	3.7	-0.4	Production Processes	-6.2	5.1	-0.6
								Mobilisation	-6.2	5.5	-0.4
								Distribution	-	-	-
				Technology	-9.0	7.6	-0.7	Innovation	-4.8	5.6	0.4
								Efficiencies	-12.3	8.3	-2.0
								Techno-Economics	-7.8	7.2	-0.3
				Energy Sector	-2.1	2.8	0.4	Bioenergy	-1.4	2.0	0.3
								Energy System Performances	-2.6	3.4	0.4
				Bioeconomy	-	-	-	Added Value Products	-	-	-
								Bioenergy Complementing Wider Sectors	-	-	-
				Land Utilisation	-9.9	9.7	-0.1	Land Characteristics	-9.1	9.1	0.0
Natural System	-4.1	2.9	-0.6	Land	-6.7	3.9	-1.4	Soil	-6.6	5.2	-0.7
								Ecosystems	-5.9	2.3	-1.8
				Air	-	-	-	PM Pollutants	-	-	-
								Oxide Pollutants	-	-	-
								Heavy Metals	-	-	-
				Water	-2.8	1.5	-0.7	Water Use & Efficiency	-2.4	1.6	-0.4
								Water Quality	-2.5	1.1	-0.7
								Water Systems	-2.9	1.5	-0.7
Climate Change	-6.2	10.0	1.9	Governance	-6.4	12.3	3.0	Climate Action	-6.9	11.4	2.3
								Standards	-5.0	11.7	3.4
				Emissions	-6.7	5.5	-0.6	Whole Life Cycle Emissions	-6.7	4.6	-1.1
								Land & Carbon Stocks	-5.7	5.8	0.1
								Counterfactual Considerations	-5.4	4.9	-0.3
				Energy Systems	-	-	-	Replaced Fuels	-	-	-

providing a positive influence on land (soil and ecosystems) and for water systems (quality and management). In contrast the results demonstrate the leading sustainability risks from energy crops are also strongly linked to the land and natural systems. For example risks are identified for water systems where unsustainable use of water occurs, and crucially to the land where there may be significant impacts to land carbon stocks if energy crops of produced at an unsuitable scale or on unsuitable lands [75].

5.2. Mapping influence of UK biomass resources on the SDGs

The bar graphs of Fig. 4 present outputs from the BSIM, mapping the potential influence of mobilising UK biomass resources as feedstocks on achieving the UN's 17 SDGs. A full breakdown of results are included within the Supplementary Materials.

Fig. 4 highlights that for a significant number of SDGs, mobilisation for UK biomass resources may provide both positive and negative influences on the SDGs. As each SDG consists a framework of separate targets, there is potential to benefit and impact different targets within the same SDG. UK resources are shown to have both positive and negative influence on SDG 8 (Economics), 9 (Industry, Innovation, Infrastructure), 11 (Cities & Communities) and 13 (Climate). Whilst UK agri-residues and energy crops may have this contrasting influence for SDG 15 (Land).

For all three biomass resource categories the mobilisation as feedstocks is shown to provide only positive influences for achieving the targets of SDG 10 (Inequalities), 16 (Institutions) and 17 (Partnerships). MSW has the potential to generate only positive influences on SDG 15 (Land), MSW and energy crops positively influence SDG 6 (Clean Water) and 3 (Health & Wellbeing), and MSW and agri-residues for SDG 2 (Hunger). In contrast the mobilisation of each resource category as feedstocks is shown to provide only negative influence on SDG 7 (Clean Energy). This finding should be taken within the context of the scope of the UK biomass resource case studies which were restricted to resource mobilisation (production/harvesting/sourcing) with the assessment ending at the 'farm gate', therefore BSIM sustainability issues that would assess onward low carbon energy resulting from use of the feedstocks are not included within these analyses. Graph-b also highlights that potential mobilisation of UK agri-residues may have only negative influences for SDG 6 (Clean Water).

5.3. Sustainability performance of bioenergy from coffee agri-residues in Colombia

Radar graphs presented in Fig. 5 map the balance of overall sustainability performance of the full Colombia bioenergy value chain case studies, where coffee agri-residue are used to generate bio-electricity to replace either grid or diesel electricity. The design of these graphs reflects that described for Fig. 3. Fig. 5 is supported by full BSIM output data included within the Supplementary Materials.

The analyses for the Colombia case studies clearly demonstrate that on balance there is greater potential for sustainability benefits, in some case far outweighing risks. The sustainability performances where diesel electricity is replaced are shown to be slightly more beneficial in certain areas compared to where grid electricity is replaced. Although the overarching trend is that bioenergy from coffee agri-residues may provide overall benefits to people, for development, for natural system and for climate change and emissions. Closer review of the outputs highlights that there may be particular benefits for people through job creation, increased

Table 6
Sustainability Performance Scores, sourcing UK energy crop biomass resources as feedstocks for bioenergy.

Sustainability Categories Index Scores				Sustainability Theme Index Scores				Sustainability Indicator Index Scores			
	SPS^r	SPS^b	SPS		SPS^r	SPS^b	SPS		SPS^r	SPS^b	SPS
People	-7.0	8.6	0.8	Health	-3.8	3.7	0.0	Health & Wellbeing	-	-	-
								Food Systems	-9.0	9.0	0.0
				Livelihoods	-7.5	7.8	0.1	Land Management	-11.6	8.3	-1.7
								Decent Work	-	-	-
								Jobs & Skills	-7.5	13.0	2.8
								Change in income	-7.4	10.4	1.5
				Society	-1.7	2.2	0.3	Equality	-6.3	9.4	1.6
								Peace, Justice & Strong Institutions	-	-	-
								Partnerships	-	-	-
								Energy Access	-	-	-
Development	-11.9	14.3	1.2	Economy	-6.9	8.8	1.0	Economic Performance	-9.4	12.0	1.3
								Economic Stimulation	-3.9	5.2	0.6
				Infrastructure	-9.4	13.7	2.1	Infrastructure Requirements	-8.7	12.8	2.1
				Feedstocks	-6.8	3.2	-1.8	Production Processes	-6.2	2.5	-1.8
								Mobilisation	-12.5	6.7	-2.9
								Distribution	-	-	-
				Technology	-10.7	6.4	-2.2	Innovation	-5.8	6.1	0.1
								Efficiencies	-12.3	4.1	-4.1
								Techno-Economics	-11.6	7.9	-1.8
				Energy Sector	-3.9	3.9	0.0	Bioenergy	-1.5	2.1	0.3
								Energy System Performances	-6.1	5.3	-0.4
				Bioeconomy	-	-	-	Added Value Products	-	-	-
								Bioenergy Complementing Wider Sectors	-	-	-
				Land Utilisation	-11.4	13.1	0.9	Land Characteristics	-10.5	12.3	0.9
Natural System	-5.2	9.5	2.1	Land	-6.0	10.9	2.5	Soil	-5.3	10.4	2.5
								Ecosystems	-5.9	10.2	2.1
				Air	-	-	-	PM Pollutants	-	-	-
								Oxide Pollutants	-	-	-
								Heavy Metals	-	-	-
				Water	-6.0	6.9	0.5	Water Use & Efficiency	-8.8	6.4	-1.2
								Water Quality	-4.1	5.1	0.5
								Water Systems	-4.5	8.3	1.9
limate Change	-6.4	9.7	1.7	Governance	-6.8	11.0	2.1	Climate Action	-8.0	10.9	1.5
								Standards	-4.7	9.6	2.5
				Emissions	-6.7	6.2	-0.2	Whole Life Cycle Emissions	-4.9	5.1	0.1
								Land & Carbon Stocks	-7.1	5.7	-0.7
								Counterfactual Considerations	-6.3	6.6	0.2
				Energy Systems	-	-	-	Replaced Fuels	-	-	-

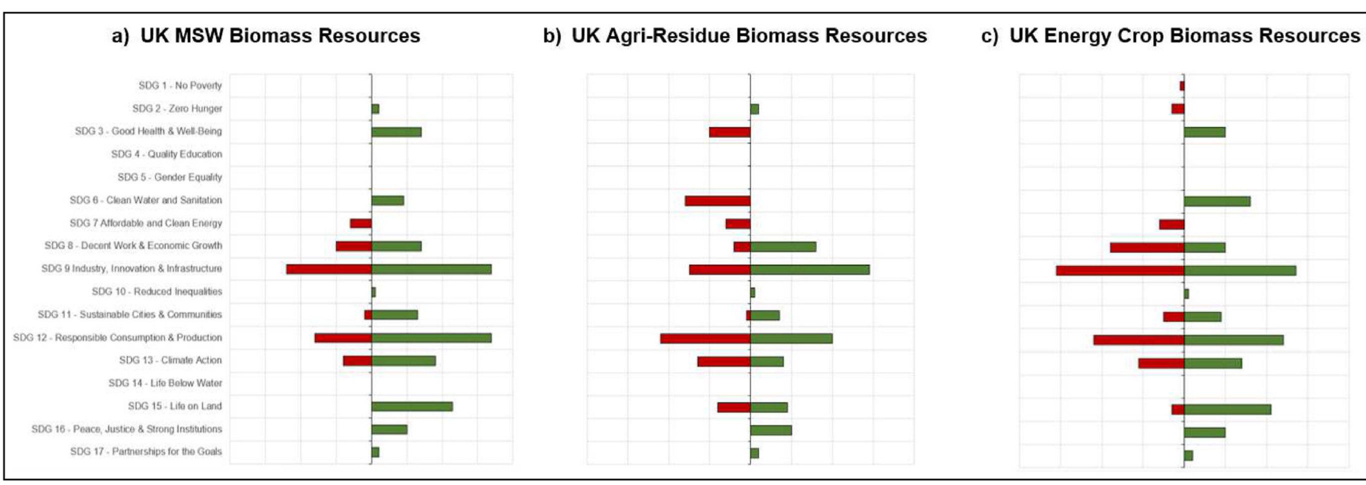

Fig. 4. Mapping Bioenergy's Potential Influences on the UN SDGs, sourcing UK biomass resources for bioenergy.

income and through Government/industry/community partnerships. Sustainability benefits may also be gained through increasing access to energy, particularly where bioenergy replaces diesel technologies.

Sustainability risks are identified linked to the financial capacity required to adopt bioenergy and the reliance on economic support measures, particularly relating to the potential capital expenditure costs. However, the analyses shows that these risks within the Development category are outweighed by the potential economic benefits gained through such projects, particularly linked to the stimulation they may provide for wider sectors and the benefits from resulting infrastructure.

The case study results highlight large potential benefits gained through raising awareness of energy and climate issues and through contributing to national targets. However, there are also noticeable differences in the potential emissions performances between the two case studies. The analysis highlights there is a risk of emissions linked to the pre-treatment and processing of coffee agri-residues which can be energy intensive [73], however there is still an overall sustainability benefit as the whole life cycle emission

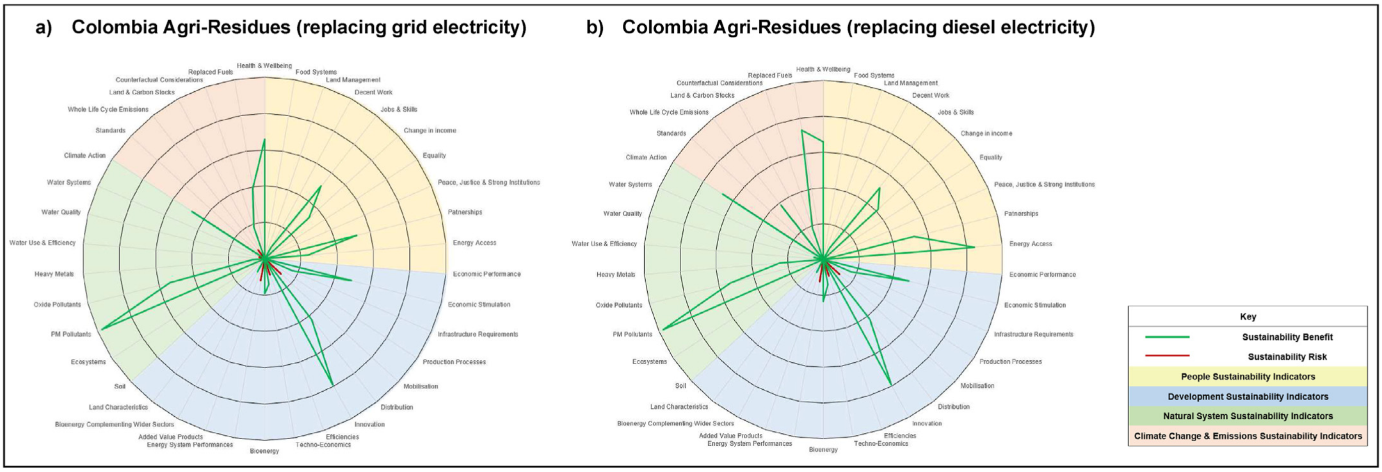

Fig. 5. Sustainability Mapping, assessment of the balance of potential sustainability risks and benefits of sourcing Colombian coffee agri-residues to produce bio-electricity to replace grid and diesel electricity generation.

of the resulting bioenergy are far less than that of diesel electricity. Although when the bioenergy replaces grid electricity in Colombia the comparative performance is far less favourable, linked to the high proportion of low carbon hydro power available through the Colombian electricity grid (71% as of 2019 [76]).

5.4. Mapping influence of bioenergy from colombian coffee agri-residues on the SDGs

The bar graphs of Fig. 6 present outputs from the BSIM mapping the potential influence of bioenergy generated from Colombian coffee agri-residues on the SDGs. A full breakdown of results are listed within the Supplementary Materials.

The graphs highlight potential influence on 13 of the SDGs with both possible positive and negative impacts. For a significant number of SDGs Fig. 6 shows that the use of Colombian coffee agri-residues for bioenergy may provide both positive and negative influences on the SDGs. However in each case the scale of the potential positive influence far exceeds the negative – indicating the bioenergy projects would contribute to achieving far more individual targets within the SDGs than preventing their achievement. The bioenergy projects would have varying influence on SDG 8 (Economics), 9 (Industry, Innovation, Infrastructure), 11 (Cities & Communities), 12 (Responsible Production), 13 (Climate) and 15 (Land).

For each case study the analyses shows there is potential to provide only positive influences for achieving the targets of SDG 3 (Health & Wellbeing), 6 (Clean Water), 7 (Clean Energy), 10 (Inequalities), 16 (Institutions) and 17 (Partnerships).

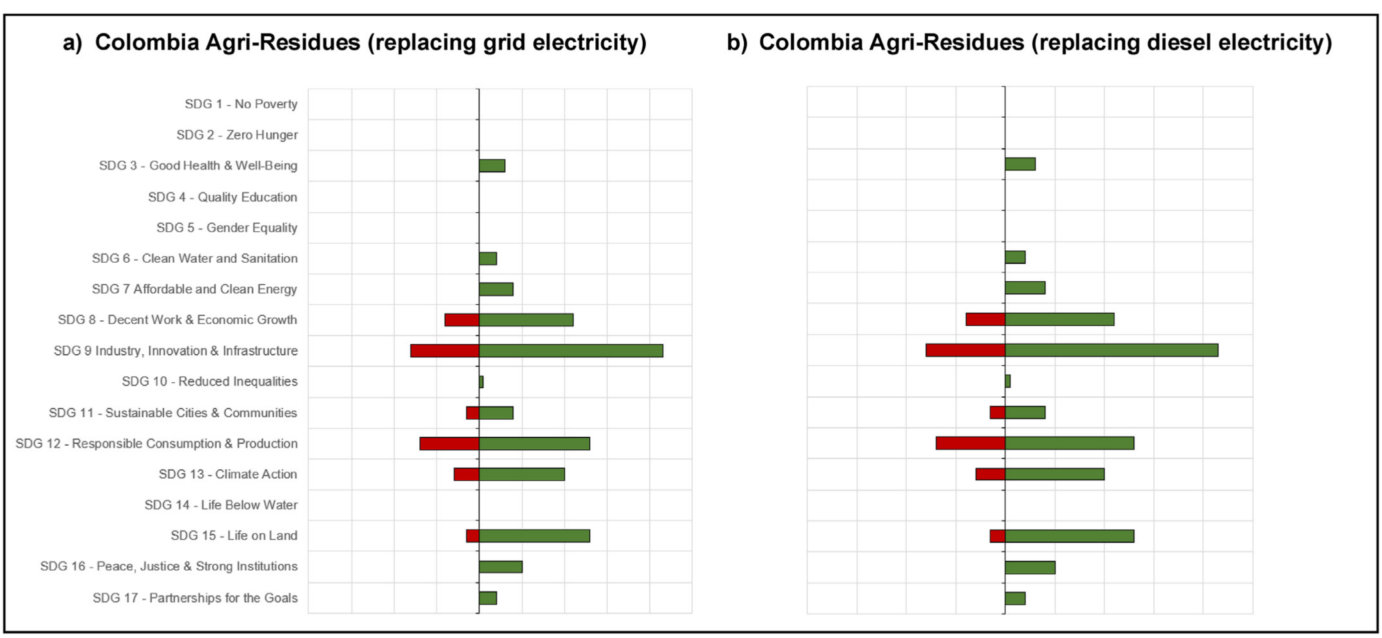

Fig. 6. Mapping Bioenergy's Potential Influences on the UN SDGs, sourcing Colombian coffee agri-residues to produce bio-electricity to replace grid and diesel electricity generation.

6. Discussion

6.1. The value of mapping sustainability performances

The BSIM output results presented in this research demonstrate the value in undertaking full sustainability mapping appraisals of bioeconomy projects. The appraisals against 126 sustainability issues provides valuable insights into sustainability themes far beyond the key issues mandated by regulation. Presentation of the results in the radar graphs of Figs. 3 and 5 provides clear visual analyses of the leading sustainability risks and benefits for given projects. This may be used to develop targeted actions to mitigate risks or maximise benefits. It is also clear from Figs. 3 and 5 that sustainability is not a binary concept but a balance of risks and benefits. In reality it is likely that all projects will encompass trade-offs that will need to be considered when exploring the concepts of sustainability and when determining what a 'sustainable project' actually is.

Through mapping sustainability performances at different resolutions as enabled within the BSIM, it is possible to construct a deeper overall picture of sustainability. As documented through the outputs presented in Tables 4–6, the sustainability of the case studies is shown to be a construct of an intricate balance of risks and benefits. Mapping sustainability at different resolutions allows better rationalisation of potential risks. For example, the potential risks linked with the capital costs of using wastes as a feedstock (Table 4) may be considered with greater maturity by also highlighting the potential benefits that may be gained by the economy through the positive influences of infrastructure and added value products for the bioeconomy. Therefore, risks may become more acceptable when weighed against broader benefits potentially gained. The results in Table 6 for energy crops also provide a valuable insight into how projects may generate broad ranging benefits – by accepting risks such as capital costs there is potential for far reaching benefits outside of development issues, for example for: livelihoods (jobs, skills), society (equality), land systems (soil and ecosystem health), water systems (quality, ecosystem services), climate governance (targets, standards) and GHG emissions performance.

The BSIM also has limitations that need highlighting when assessing outputs. These stem from the intrinsic design of the model but also the way in which it may be used. For example, the weightings of each sustainability issue are fundamental to the calculations used to assess sustainability performance. The built-in default weightings have been developed through stakeholder engagement, however these values will be reflective of the knowledge and opinions of these stakeholders, which may align or differ from broader consensus. The same is true when calibrating the model to assess a given case study, the specific calibration values will reflect the views and knowledge of the model user(s). These limitations should be qualified when using outputs to draw broader conclusions about bioenergy sustainability. The BSIM was also designed based on index values to represent degrees of sustainability risk or benefit. The use of these index values provides a mechanism to highlight varying performance within a project or when comparing projects. These values may have limited external use and should not be used to form assumptions, for example the number of jobs potentially created.

However, as an overall approach this research enforces an argument that sustainability mapping should be used more extensively, potentially to develop a comprehensive evidence base of the environmental benefits and risks for different bioenergy case studies. It being critical for the future momentum of the sector to build areas of scientific consensus, to clearly communicate sustainability implications, and to also provide evidence of the many sustainability benefits that may be gained and how these outweigh the sustainability risks [77]. Mapped sustainability risks potentially being mitigated through a combined approach of governance by regulations to drive change, by voluntary measures championed by relevant industries and through continuing research that aims to identify and prevent emerging risks [78].

6.2. Bioenergy sustainability beyond emissions & land

Key bioenergy sustainability legislation such as the RED, target the important themes of carbon stocks, emissions and biodiversity – these are comparatively 'easy' to quantify, arguably represent the greatest risks to large scale bioenergy and play a key role for climate change mitigation. For sustainability criteria to be truly effective there is an argument for expanding the themes covered to also provide protections for water, soil, air and social issues etc [24]. The narrow scope of legislation and that of a number of voluntary certification schemes, means many wider sustainability themes gain no coverage. This is a trend reflected across bioenergy sustainability studies where there has been overwhelming concentration on environmental sustainability limited to GHG emissions and the provision of energy [79]. There has been growing interest in economic dimensions, but focus on sustainability issues such those providing risks and benefits for people and society have been addressed less vigorously [80].

Mapping sustainability performance of bioenergy case studies against the 126 individual sustainability issues within the BSIM clearly highlights that sustainability goes far beyond emissions and land. Developing regulations to prevent the greatest potential risks is undoubtedly the correct approach and it is hard to defend against any argument for expansion to include themes such as water protection. In contrast to the argument for expanding sustainability criteria to include other issues where there is potential for risk, the sustainability mapping outputs presented in this paper suggest there should also be an argument for promoting and maximising benefits. For example, the sustainability maps within Fig. 5 each highlight that bioenergy projects in Colombia may provide overwhelmingly positive influences on factors such as job creation and income, stimulation of wider sectors of the economy through the positive influences from innovation, infrastructure development and provision of increased access to energy. Equivalent structured support for wider sustainability themes such as these would ensure the maximum potential benefits are gained, also making bioenergy the comprehensive driver of sustainable development as evidenced by the close links between bioenergy and the SDGs.

6.3. Bioenergy as a mechanism for achieving the UN SDGs

The United Nation's 17 Sustainable Development Goals (SDGs) are each developed on a framework of sustainability targets that provide a shared blueprint for countries to achieve their development sustainably. The 2030 Agenda on Sustainable Development [81] provides the internationally agreed framework of quantitative evaluation of achieving sustainability goals, through which countries are expected to report their progress. It is over the same timeframe to and beyond 2030 that bioenergy is also expected to be most keenly targeted to provide the 'stepping stone' technology that enables the transition technology away from fossil fuels [82]. This research demonstrates that bioenergy is intrinsically linked to the SDGs and sustainable bioenergy can provide a mechanism to drive their progress. Efficient use of biomass resources and the broader sustainability of bioenergy projects being can be highly influential for achieving many of the SDGs [83].

Fig. 2 highlighted that bioenergy projects have the potential to influence all 17 SDGs, whilst the graphs within Figs. 4 and 6 demonstrate that this influence could be overwhelmingly positive. The research also identified the potential for negative influences on the SDGs as shown within Fig. 6 for SDG 9 (Industry, Innovation & Infrastructure) and SDG 12 (Responsible Consumption & Production), highlighting the ongoing risks for bioenergy projects stemming from sustainable supply issues and initial capital costs – potential detrimental impacts for wider sustainable development ambitions.

As all SDGs interact with each other [84] the full influence of bioenergy projects may be greater than that suggested in this research. As the bioenergy sector and related industries of the bioeconomy continue to grow it will be important to continue evaluating links with the SDGs. As the influence of bioenergy on certain SDGs is greater than others (Fig. 2) it would be valuable to establish the extent to which the benefits to certain SDGs has consequential positive influence on linked SDGs. This provides a strong argument for sustainable bioenergy to be prioritised as key driver of progression towards achieving many of the SDGs [83].

7. Conclusions

Demand for biomass resources will continue to grow as bioenergy is increasingly targeted within energy strategies. Sustainability of bioenergy is a primary issue for commercial scale bioenergy projects, with potential to generate both benefits and risks for people, development, natural systems and climate change. This paper introduces a new sustainability mapping framework, designed to provide a flexible tool to map the performances of biomass resources, supply chains, technologies and/or whole value chains against 126 indicators of sustainability. Also mapping the linkages between bioenergy projects and the United Nations Sustainable Development Goals (SDGs). The value of mapping the sustainability of bioenergy is demonstrated through analyses of two case studies: analysing the sustainability performance of using UK biomass resource for bioenergy, also; the sustainability performance of using agri-residues in Colombia to provide bio-power. The key conclusions are:

- Sustainability of bioenergy covers far more issues than those targeted within legislation – where land, carbon and biodiversity are prioritised. Legislation focuses on preventing the perceived greatest risks. However, it is within many of the wider sustainability themes where bioenergy can provide the greatest benefits, and there is a strong argument to also develop frameworks to maximise benefits gained.
- Mapping sustainability is a valuable tool to identify the leading risks and benefits to target actions to mitigate risks and to maximise and promote benefits.
- Bioenergy sustainability is a system of trade-offs and an unlikely end destination. Every bioenergy project will generate both sustainability risks and benefits. Mapping sustainability at different resolutions and analysing the trade-offs enables greater rationalisation of potential risks through also identifying the potential broader benefits gained.
- Bioenergy is intrinsically linked to the SDGs, more so than other renewable technologies. These relationships should be further explored as bioenergy could become a mechanism to be prioritised as a global priority in working towards development.

CRediT authorship contribution statement

Andrew Welfle: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft. **Mirjam Röder:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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