Literature review on social and economic sustainability of bioenergy systems

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Executive Summary

This stock-taking report has been carried out by IEA Bioenergy with the contribution of different Tasks under this Technology Collaboration Programme (TCP). It undertakes a broad review of existing literature examining indicators to measure social, economic, and environmental benefits associated with bioenergy production. The goal of this report is threefold: (1) to update the current state of knowledge regarding the benefits and trade-offs associated with bioenergy, (2) to determine which indicators are most widely used to track various social, economic, and environmental impacts, and (3) to relate indicators to specific indicators associated with Sustainable Development Goals. The report considered all bioenergy systems, including small- and large-scale recovery of biomass for heating and cooking, the recovery of residues or purpose-grown crops/trees for energy generation (heat and electricity), and the processing of various biomass feedstocks into liquid fuels for application in ground, aviation, or marine transport. This report has been carried out in part as a response to concerns raised by members of the public, and emphasized in the media, over the sustainability of bioenergy systems as part of a transition towards a cleaner, more sustainable economy.

To support this work, a virtual workshop was held on 17 September 2024 with approximately 40 experts drawn from the authors of literature included within this report. The workshop delivered key insights, including the need to use multiple indicators that reflect the context of specific projects, the need to incorporate additional indicators, and the important role that IEA Bioenergy has in guiding methodologies for measuring specific indicators.

Social sustainability: In total, ten indicators were assessed. Participants at the workshop focused on particulate emissions, land tenure, and risk of catastrophe as critical measures. In the literature, the impact of bioenergy on food systems and the impact of bioenergy use on human health and indoor air quality are well covered. There is a moderate amount of literature on indicators including access to clean water, land allocation, land tenure, and public opinion. Some indicators are not well addressed in the literature, including uptake of bioenergy by local populations, adherence of bioenergy to local regulations, the role of bioenergy in circular economies, and the contribution of bioenergy supply chains to addressing the risk of catastrophes (e.g. wildfires, disease, and pest outbreaks) within the supply chain.

Economic sustainability: In total, fourteen indicators were assessed. Indicators highlighted at the workshop include access to bioenergy along with cost and price volatility, the financial viability of projects, the cost of CO2 abatement, and the community benefit that accrues with these projects. Some indicators are covered well in the literature, including economic productivity, per capita income, numbers of jobs, financial viability, cost of CO2 abatement, and gender equality (with respect to fuelwood gathering). Others are poorly covered by existing studies, including trends in work hours, access to bioenergy along with cost and price volatility, research and development investment, land tenure and gender-based roles in land tenure, education, and community benefit.

Environmental sustainability: Within studies that covered social and economic sustainability issues, a total of five environmental indicators were often included. Some of these were well covered in the literature, including trends in fossil fuel use, energy efficiency, and carbon emissions. Others have less documentation, including the relation between bioenergy systems and soil carbon or soil degradation (the impacts of bioenergy on biodiversity is not well document), as well as the link between bioenergy systems and eutrophication in marine waters. These indicators are incorporated in this study because they are often linked to indicators of social and economic sustainability, but do not represent the full range of environmental indicators being used.

Key priorities for future work

Overall, the primary priority of IEA Bioenergy should be to work with stakeholders to improve methodologies for tracking these indicators. Common elements include:

(a) Better determination of system boundaries for project assessment
The collection of bioenergy data is diverse and lacks consistency across the range of studies considered within this report. IEA Bioenergy can provide guidance to stakeholders in determining appropriate boundaries for these studies. As an example, many studies equate the introduction of bioenergy production capacity with increased local access to renewable energy without providing data on the uptake, or accessibility, of the bioenergy product within the local marketplace.

(b) A more consistent approach for evaluating the impact of bioenergy supply chains on local economies. As an example, collecting data regarding jobs could be made easier if the typology of employment were clearer (e.g., temporary, construction, operations, etc.) and if the relation of employment to supply chain was defined (e.g., feedstock supply, feedstock processing, energy production, etc.). IEA Bioenergy can provide guidance on how to understand the various components that contribute to local economies and highlight best practices in assembling data to understand these impacts.

(c) More guidance on functional units for assessment to improve comparisons between different bioenergy systems. This is particularly important when looking at a wide range of bioenergy systems that operate at different scales. Some common measurements – for example, investment per unit bioenergy generated, or per unit of carbon emission mitigated – would be very helpful in providing points of comparison between different bioenergy options. IEA Bioenergy can provide guidance on the best functional units to allow these comparisons and thus promote the most sustainable bioenergy solutions.

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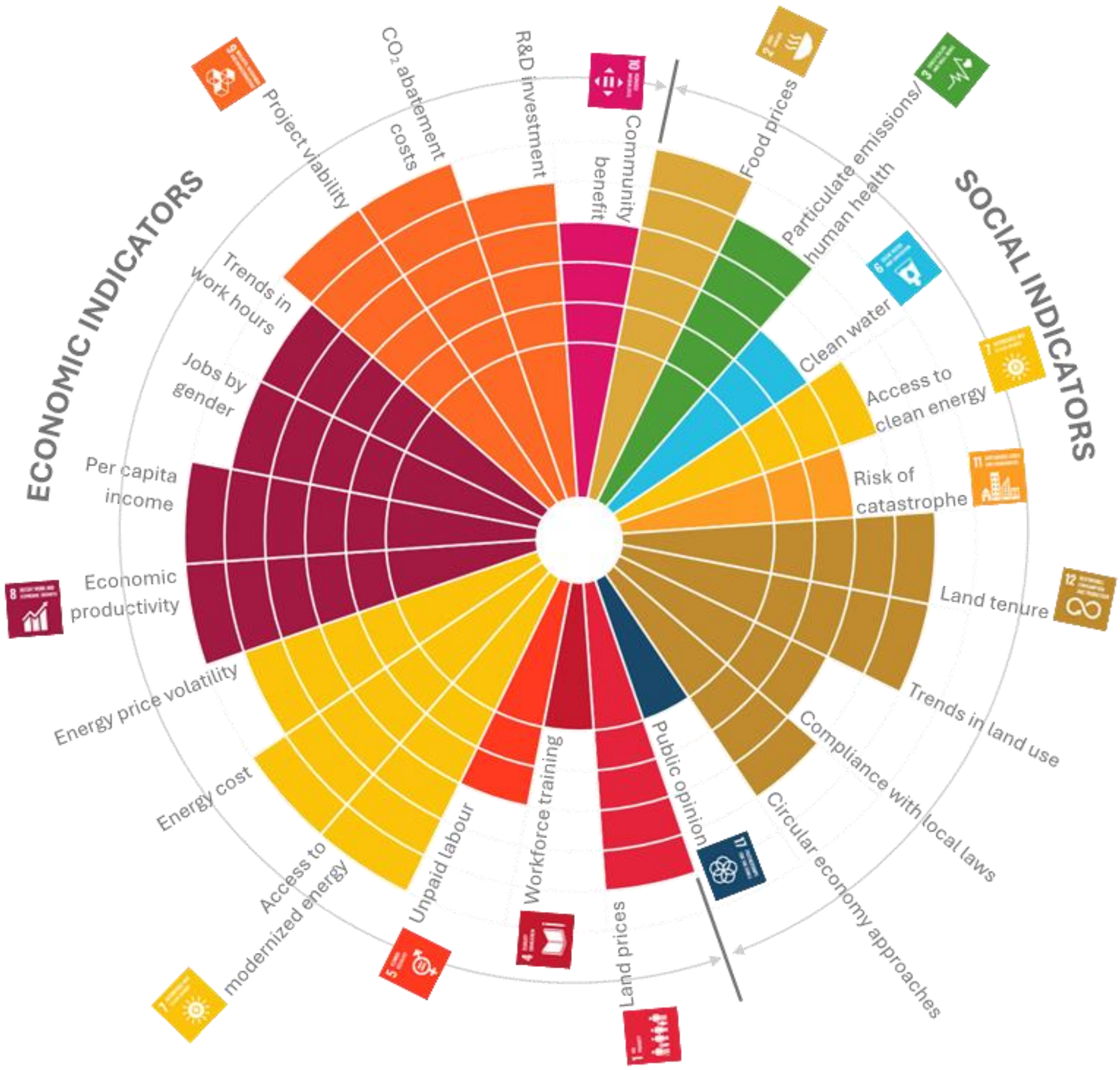
Graphical Summary

In this figure, indicators are categorized by their relation to specific Sustainable Development Goals (SDGs) and grouped to social or economic measures. The size of the bar indicates increasing correlation between indicators and SDG datasets **and/or** increasing availability of data. The larger the bar, the greater the correlation and/or access to studies; shorter bars indicate areas that are not well correlated to SDGs or are not well documented in the literature. In total, 10 indicators were assessed for social sustainability, which in turn link to 7 SDGs. As well, 14 indicators for economic sustainability are assessed, linked to 7 SDGs. In the body of this report, 5 indicators for environmental sustainability are also considered, but they are not incorporated into this figure.



Introduction

Key parameters about the sustainability of bioenergy systems have been studied for a number of years. A study done in 2013 highlighted the importance of communication, and the difficulty with relying upon scientific journal articles to inform policymakers and decision-makers looking to develop bioenergy and bioproduct systems (Dale et al. 2013b). Studies have highlighted the importance of assessing bioproduct sustainability in the face of rapid expected growth, and the value of developing standardized assessments on environmental, social, and economic impacts of bioenergy production (Burli et al. 2016, Correa et al. 2019). Critically, it's important that benefits be quantified; many studies have promoted biofuels or bioproducts as a means of developing socio-economic benefits at both the local and national scale, but suffer from vague statements of what these benefits actually will be (Dos Santos et al. 2014). Recent work has pointed out the importance of improving the quantification of specific indicators for the social and economic performance of bioenergy, particularly where few or no indicators have been widely explored (Brinkman et al. 2019).

In the energy transition, bioenergy has been estimated by some to have a total potential of 100,000 PJ/year (Aghahosseini et al. 2023); bioenergy can be produced through a number of platforms (see Box 1). While this is a restricted figure and a small portion of the total global energy demand, it still represents a very large potential use for biomass resources. Multiple reports have thus generated comprehensive lists of indicators that can be used to assess the sustainability of bioenergy systems (McBride et al. 2011, Dale, Kline 2013). For example, a system of twelve indicators to assess sustainability was developed in a series of works (Dale et al. 2013a, Efroymson et al. 2013), including three economic indicators, three social indicators, and six environmental indicators; some of these indicators incorporated more than one measure, and in most applications these indicators have been used in a relative fashion (i.e. compared to a reference system). In 2011, the Global Bioenergy Partnership Secretariat generated a report with an extensive list (GBEP 2011). Burli et al. also highlighted a wide range of specific indicators (Burli et al. 2016).

Box 1 – Bioenergy systems under consideration

This report was not limited to a specific bioenergy system. Thus, the systems examined through the lens of specific indicators range from small-scale, non-industrial bioenergy applications (e.g., household cooking and heating) through mid- to large-scale, industrial applications including industrial heat and electricity generation, or the production of solid biofuels (e.g., wood pellets) for power generation or liquid biofuels (e.g., ethanol or biodiesel) for transport, including ground, marine, and aviation purposes. The feedstocks examined in the literature covered by this report include agricultural crops (cereals, oilseeds, etc.), agricultural residues, forest residues from harvests (tops, branches, non-merchantable wood, etc.) and from forest product manufacture (bark, chips, etc.).

A number of other recent studies have provided a comprehensive review of indicators that would be useful to support bioenergy development (McBride et al. 2011, Repo et al. 2011, Diaz-Chavez 2014, Manara, Zabaniotou 2014, Iacovidou et al. 2017, Szarka et al. 2017, Zabaniotou 2018). Interestingly, recent work surveying 122 experts across 23 countries suggests that social attributes are given the lowest priority among different sustainability criteria (Mola-Yudego et al. 2024). This work suggest that key measures include environmental indicators (reducing GHG emissions, protecting ecosystems and biodiversity) and economic measures (utilizing local resources efficiently); the only social measure highly ranked was revitalizing rural areas. This study also highlighted the importance of localized data in understanding the benefits of bioenergy supply chains (Mola-Yudego et al. 2024).

Fürtner et al. explored a methodology for determining indicators that could be used in social life cycle assessment (SLCA) considering a short-rotation coppice case study in Slovakia (Fürtner et al. 2021). This study suggested that workers, followed by community, value chain actors and finally broader members of society are the key stakeholder groups that should be consulted. Workers prioritized indicators including safe working conditions, health and safety, forced labour, child labour, fair salary, and equal opportunity. Local community prioritized respect of Indigenous or local community rights, regional value creation, economic development, safe working conditions, community engagement, and local employment. Society focused on contributions to economic development, corruption, and meeting sustainability goals, while value chain actors prioritized supplier relations, respect for intellectual property, and fair competition. Other authors have also suggested that LCA tools are essential to tracking bioenergy supply chain sustainability (Hiloidhari et al. 2023). Identifying stakeholders to consult regarding potential indicators can be challenging; one study addressed this challenge by using agent-based modeling to connect stakeholders across a miscanthus-based cellulosic bioproduct chain in Illinois (Yang et al. 2022).

Multiple studies relate indicators of a sustainable bioenergy value chain to the Sustainable Development Goals (or SDGs), now in wide use as a means of tracking progress towards the more sustainable use of natural and human resources for the betterment of global society (McCollum et al. 2018, Blair et al. 2021, Calicioglu, Bogdanski 2021, Hiloidhari et al. 2023) (see Box 2).

Box 2 – Sustainable Development Goals

A fundamental organizing principle used within this report is the framework provided by the Sustainable Development Goals (SDGs), which were adopted by the United Nations in 2015. The 17 SDGs represent one of the most holistic overviews of sustainability currently in use and are characterized by a set of 169 discrete targets and 231 unique proposed indicators, which governments and institutions can apply to evaluate their own progress towards sustainability (UN Statistics Division 2022). The 17 SDGs include (1) No Poverty, (2) Zero Hunger, (3) Good Health and Well-being, (4) Quality Education, (5) Gender Equality, (6) Clean Water and Sanitation, (7) Affordable and Clean Energy, (8) Decent Work and Economic Growth, (9) Industry, Innovation, and Infrastructure, (10) Reduced Inequalities, (11) Sustainable Cities and Communities, (12) Responsible Consumption and Production, (13) Climate Action, (14) Life Below Water), (15) Life on Land, (16) Peace, Justice and Strong Institutions, and (17) Partnerships for the Goals. As such, the SDGs comprehensively address aspects of environmental, social, and economic sustainability.

A study in Mexico linked assessment of socio-economic benefits to SDGs using a case study of a community managed forestry operation used to supply local bioenergy options (Martinez-Hernandez et al. 2024). In this study, indicators related to these benefits were selected, co-developed, and weighted using a participatory approach beginning with identifying the stakeholders involved, who are invited to help select indicators from the literature which in turn are tested for their ability to quantify local impacts and important contextual measures of bioenergy benefits. Workshops and surveys can be used to finalize the list for evaluation. Calicioglu and Bogdanski (2021) also considered the use of SDGs to track progress towards the sustainable bioeconomy, and suggested that four clusters of SDGs could be assembled. These include a grouping of SDG 1, SDG 2, SDG 5, SDG 8, and SDG 10 to consider aspects of regional development (both economic and social); a group of SDG 4, SDG 6, SDG 8, SDG 11, and SDG 12 to consider the ecological aspects of bioeconomy feedstock recovery; a group of SDG 9 and SDG 17 to look at international competitiveness, trade, research, and development; and finally, a group of SDG 3, SDG 7, and SDG 13 to address global environmental issues including emissions and material sustainability (Calicioglu, Bogdanski 2021).

Blair et al. (2021) suggested that the impacts associated with bioenergy supply chains are most closely related to SDG 2 (Zero hunger), SDG 7 (Affordable and clean energy), SDG 8 (Decent work and economic growth), SDG 9 (Industry, innovation, and infrastructure), SDG 12 (Responsible consumption and production), SDG 13 (Climate action), and SDG 15 (Life on land). SDGs that had a moderate likelihood of being linked to biomass supply chains included SDG 1 (No poverty), SDG 3 (Good health and well-being), SDG 6 (Clean water and sanitation), SDG 10 (Reduced inequalities), and SDG 11 (Sustainable cities and communities). The SDGs least likely to be linked to biomass supply include SDG 4 (Quality education), SDG 5 (Gender equality), SDG 14 (Life below water), SDG 16 (Peace, justice and strong institutions), and SDG 17 (Partnerships for the goals). This study notes these clusters but does not use them to organize the SDGs within social, economic, and environmental categories.

Work by Vera et al. (2022) examined the ability of bioenergy systems to meet various SDGs and explored synergies and trade-offs between different SDGs. This study found that while synergies can exist between some SDGs – for example, a number of environmental SDGs may be met using perennial crops in temperate zones, but there may be trade-offs between these systems and food security or water availability (Vera et al. 2022).

SDGs can be a very helpful tool for understanding the impacts of bioenergy systems as these goals, and the indicators behind them, are increasingly used by countries and institutions to track their progress towards improved sustainability. Understanding how different measures of bioenergy sustainability intersect with the SDGs provides insight into which measures might be more important within the local context. In some nations (e.g., Canada, Sweden, etc.) indicators related to SDG 13 (Climate Action) might be more useful, as these nations are focused on emissions reduction. In other nations, particularly in the global south, measures related to SDG 1 (No Poverty) or SDG 2 (Zero Hunger) may be more relevant and of higher local importance.

In this study, a broad review of existing literature examining social, economic, and environmental benefits associated with bioenergy production is carried out. The goal of this study is threefold: (1) to update the current state of knowledge regarding the benefits and trade-offs associated with bioenergy production and provide a thorough review of literature that addresses these issues, (2) to determine which indicators are most widely used to track various social, economic, and environmental impacts associated with bioenergy systems, and (3) to more closely relate the indicators being tracked in the literature to specific indicators associated with the SDGs. The purpose of linking bioenergy sustainability indicators to SDGs is to identify opportunities for data sharing, as a long list of targets and indicators for SDGs have been proposed, and in many cases these datasets may shed light on bioenergy supply chains. This method or organization also simplifies the task of reviewing which indicators of sustainability are most relevant in the local context, as individual countries generally identify SDGs of particular focus and thus indicators related to these SDGs might provide better insight. This work also highlights gaps in methodologies for measuring indicators.

September Workshop

On 17 September 2024, approximately 40 experts with experience measuring the social and economic impact of bioenergy supply chains gathered for an online workshop hosted by IEA Bioenergy. The workshop was widely advertised and personalized invitations were sent to authors of reports incorporated in the draft copy of this report. The workshop ran for slightly more than two hours and was facilitated by the author of this report.

At the workshop, an overview of this scoping report was provided to the audience, who were then asked to provide their input on the most important indicators for measuring social and economic impacts, to identify any gaps in the measures that were incorporated in the draft report, and to comment on the challenges in assessing these indicators. Breakout rooms were used to facilitate the conversation with a report-back mechanism. Following the breakouts, a more general conversation on challenges with measuring social and economic sustainability took place.

The conversations at this workshop provided important insights. One of the most important observations was that all of the indicators included in this scoping report are useful measures of bioenergy supply chain sustainability. No single indicator was identified as being more important than all others, although participants did favour some indicators over others. Several gaps were identified as described below. Finally, the participants provided valuable guidance for future work in this space.

FINDING 1 – NO SINGLE INDICATOR OF BIOENERGY SUSTAINABILITY

As mentioned above, all indicators incorporated within this report were found to be important measures, although some indicators were highlighted by participants. In measuring **social sustainability**, indicators that were particularly critical to track included particulate emissions, land tenure, and the risk of catastrophic disruptions. The potential impact of particulates on human health creates an overriding concern that can quickly become the focus of discussions about establishing new bioenergy facilities. Land tenure, and the industrialization of bioenergy supply chains, was also identified as a potential challenge. The vulnerability of bioenergy systems to disruption from fire, pests, and disease were flagged, with participants mentioning the mountain pine beetle infestation and recent wildfires as being of concern. There is high perceived risk associated with these disruptions, particularly as bioenergy systems become more important components of a regional or national energy system.

In measuring **economic sustainability**, indicators that were found particularly important included community benefit, access to modernized energy, energy cost, and energy price volatility. Community benefit was linked strongly to the role of community in developing these projects; participants highlighted the need for community involvement at all stages, and suggested that projects led by communities would likely be more sustainable than those imposed on the region. Similarly, access to clean energy from bioenergy projects was highlighted as a concern, with cost and price volatility being of particular importance.

Participants noted that a focus on one or two indicators, rather than an approach which allowed different indicators to be used depending upon the project at hand, would create a number of challenges. First, limiting measures of sustainability would create opportunities for opponents of bioenergy projects to respond by using other indicators which could influence decision-makers. Second, datasets to support some of the indicators included within this report are difficult to access, or non-existent, and thus it is important that the indicators used to evaluate any single project make use of the best available data. Finally, local communities and stakeholders are the ones who are best placed to determine what indicators should be used to best represent the economic and social sustainability of a bioenergy project. These voices should lead in the conversation. Workshop participants highlighted the important role that local populations have, and stress that projects led by local communities are more likely to address local needs in a sustainable fashion.

FINDING 2 – GAPS IN THE SELECTED INDICATORS

The conversation with participants identified two important, and in hindsight obvious, gaps in the indicators presented. First was the financial viability of bioenergy projects across the entire supply chain, including feedstock generation as well as plant development and energy production. The second gap was in measuring the cost of CO_2 mitigation or abatement. Both of these indicators, which are considered measures of economic sustainability, were thus investigated and are included in the present version of the stock-taking report.

FINDING 3 – A FOCUS ON METHODOLOGY

Participants in the workshop showed strong consensus in advising that this report not attempt to identify the ‘best’ indicators of economic or social sustainability, as each bioenergy project is impacted by local considerations and must be evaluated on their own merits. To avoid being prescriptive on determining which indicator set is being used, participants in the workshop suggested that future work focus on the methods used to assess individual indicators. While this report does not attempt to identify best practices for assessing each individual indicator, the literature incorporated within this study includes a number of different approaches which can be used, and future work by IEA Bioenergy may go further to determine best practices for specific indicators which reflect the needs of specific locations and bioenergy systems.

Section 1 - Social Measures

A summary of social measures can be seen in Table 1. The SDGs related to each proposed indicator are identified. In Column A, an Asterix (*) indicates that attendees at the 17 September 2024 workshop suggested that this indicator was of particular importance. In Column B, the SDGs are categorized by the clusters identified by Blair et al. (2021), with high (H), moderate (M), and low (L) correlation to bioenergy supply chain sustainability.

Table 1 - Measures of social sustainability in bioenergy systems

A	B	SDG	Bioenergy Indicator	Selected literature
	H	2 ZERO HUNGER	Trends in food output and prices, compared with previous trends	Burli et al. 2016; Degani et al. 2022; GBEP 2011; Machado et al. 2021; Parish et al. 2018; Patel et al. 2021
*	M	3 GOOD HEALTH AND WELL-BEING	Mortality, disease due to indoor smoke trends; particulate emissions; human toxicity.	de Souza et al. 2023; GBEP 2011
	M	6 CLEAN WATER AND SANITATION	Access to clean, treated water/municipal water supply	Martinez-Hernandez et al. 2024
	H	7 AFFORDABLE AND CLEAN ENERGY	Energy diversity, access to clean energy; Infrastructure, logistics for bioenergy	GBEP 2011; Machado et al. 2021; Martinez-Hernandez et al. 2024
*	M	11 SUSTAINABLE CITIES AND COMMUNITIES	Risk of catastrophe	Parish et al. 2018
*	H	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	(1) Allocation, tenure of land used for biomass production; (2) Trends in land use; (3) Compliance with regulations including (a) storage, handling, disposal of chemicals; (b) guidelines for harvesting, storage; (c) water regulation; (4) Circular economy approaches	Burli et al. 2016; Cherubin et al. 2021; Degani et al. 2022; de Klerk et al. 2022 ; de Souza et al. 2023; GBEP 2011; Machado et al. 2021; Obidzinski et al. 2012; Patel et al. 2021; van Dam et al. 2009
	L	17 PARTNERSHIPS FOR THE GOALS	Public opinion, information sharing	Parish et al. 2018

SDG 2 - ZERO HUNGER

Indicator overview

One impact of bioenergy development that has been widely reported on is the potential relation between biomass production for energy and food pricing and availability; the 'food-vs.-fuel' debate continues to be examined by scholars, with recent studies looking at the use of marginal or underutilized lands (Djomo et al. 2023, Pulighe, Pirelli 2023), exploring the use of marine vs. terrestrial biomass (Zaky et al. 2021), or considering the implications of agricultural residue removal on greenhouse gas emissions and the overall sustainability of cropping systems (Battaglia et al. 2021). SDG 2 (Zero hunger) can thus be closely related to bioenergy supply chains. Within SDG 2, one proposed indicator is *anomalies in food prices* (2.c.1) (UN Statistics Division 2022), which would provide insight as to whether biomass production is affecting the price of food over time. GBEP (2011) and Burli et al. (2016) suggest similar indicators that track trends of food prices over time.

Key studies

It is clear from the literature that both the design of the bioenergy system and the location of the project contribute to the impacts of biomass production on food pricing. Dedicated energy crops that utilize marginalized land tend to have fewer impacts on food systems. Some of the studies reviewed, including some focused on switchgrass in the USA (Parish et al. 2016) or combined switchgrass and soybean systems in South America (van Dam et al. 2009) found no relation between bioenergy feedstock production and food security. Other studies, however, examined specific scenarios where local food production in particular was impacted even when energy crops and marginalized land are used. The effects of introducing a large-scale biorefinery onto the island of Sardinia, Italy, for example, projected declines in animal feed production under ever scenario produced (which impacts food security), and also anticipated declines in food production in all scenarios except when food production was specifically protected (Anejionu et al. 2020). This project involved the use of abandoned lands in the south of the island and included the capture of agricultural residues (straw) and the planting of a dedicated energy crop (giant reed, *Arundo donax*). The implication of this work is that location matters: isolated systems for food production may be more likely to be impacted than well-connected systems.

Other work modeled development of biomass feedstocks to support the bioeconomy to 2030 using sugarcane, soy, and forest crops in Brazil (Machado et al. 2021). This project suggested that substantive amounts of biomass could be developed, ultimately reducing crude oil demand by about 27.5 million m^3, and natural gas demand declines by 5 billion m^3. Achieving this goal would require land use change optimizing growth in agricultural crop production; under these scenarios, land use is limited based on Brazil's GHG emission reduction targets. In the bioeconomy scenarios considered, there is a drop in consumption of food, particularly meat, as pastureland is overtaken by various biomass cropping, and as food production is optimized in conjunction with biomass production. This work highlights the importance of project scale – the larger the proposed bioenergy supply chain, the greater the likelihood of impacts on food systems, even if the primary feedstock is a non-food feedstock.

It is important to note that farmers may anticipate increases in food prices associated with development of bioenergy crops, and that this expectation may affect their willingness to participate in biomass supply chains. A study in India looked at 415 households to understand socio-economic benefits associated with growing biofuels crops (Patel et al. 2021). The study site considered households across Gujarat state in western India; these households primarily relied upon agriculture for income and farmed small homesteads of less than 2 ha. The majority (96%) of these households did not know that bamboo, sorghum, or millet could be used as a feedstock for biofuels, although the majority agreed that bamboo should be used for biofuel (92%), and also agreed that millet and sorghum could be used as a biofuel (85%). About 71% of respondents thought that there might be a shortage of grain if millet and sorghum were used for biofuelsl; 74% agreed that this would affect fodder security, and 67% felt that using fodder as biofuel would affect the security of livestock, while 53% felt that it might affect household food security. 83% of households agreed that they would like to grow feedstock for biofuel given a high market price and good return on investment. These findings support the idea that farmers are more likely to join the biomass supply chain if they anticipate higher prices for their food product; this aspect of the food-vs.-fuel debate is often ignored.

In areas where biomass value chains have not been widely exploited, caution is raised about future development and potential impacts on food production. Recent work in Africa suggests that biofuels from raw biomass should be limited to feedstocks that do not compete with food production or which are drawn primarily from residues; bio-oil and syngas production are highlighted as potential new pathways for bioenergy recovery (Fertahi et al. 2023). Food security remains a key priority in Africa, alongside sustainable waste management and electrification.

The use of genetically modified feedstocks was addressed by Butkowski et al. (2017), who found that perceptions around genetic engineering depended greatly upon the end use of the feedstock. Respondents suggested that health concerns were greater than environmental concerns when discussing genetic engineering and food, while larger concerns around socioeconomics and environment were found with regards to the potential commercialization of bioenergy. Further research and development into green biotechnology that supports bioenergy, supported by informed discussion about risks and benefits, are likely to be more socially desirable than might have been expected (Butkowski et al. 2017).

Some authors took a different approach to assessing the food-vs.-fuel approach. For example, de Souza et al. (2022) measured terrestrial acidification, ecotoxicity, and eutrophication, comparing sugarcane electricity to a number of other fossil-based and renewable electricity pathways. For sugarcane electricity the results were middling; oil and coal had the worst results, while hydroelectricity had the best result. To improve the performance of sugarcane electricity, it would be necessary to reduce the amount of fertilizer utilized in the system. However, this is not a direct measure of food pricing or food security – these measures are directly related to SDG 14 and SDG 15, but may be used as a proxy for food security.

The Bioenergy and Food Security (BEFS) approach has been developed by FAO and provides a tool to help stakeholders understand the interplay between food security and bioenergy development. This approach includes a scoping stage, followed by stakeholder dialogue and capacity building, a sustainable bioenergy assessment, support for policy development, monitoring of impacts, and finally, risk prevention (FAO 2017). To date, this approach has been used in a number of countries to understand bioenergy system impacts.

Summary

This indicator is well tracked, with a number of highly relevant studies available. This review suggests that it may be possible to develop biomass feedstocks to support biorefining without impacting food security, but doing so depends on four factors: (a) location and connectivity of the bioenergy system at hand, (b) project scale, (c) expectations of landowners or leaseholders related to profit, and (d) the type of biomass being explored (i.e. food crops vs. biomass crops, residues vs. purpose-grown feedstocks). Dedicated energy crops grown on marginal lands within areas that have large, integrated, and robust food supply systems are less likely to impact food security, and can help diversify benefits within a region, particularly for the farmer or forester, as well as for landowners and community members. As the scope of the project increases, or when projects are located in more isolated or less developed regions, the likelihood of seeing impacts on food security increase. There is little consistency in the ways in which food security is assessed in the literature; while food price indices might be optimal (as per guidance from the SDG document), many studies focus on the volumes of food production or on more nebulous assessments of food security.

SDG 3 - GOOD HEALTH AND WELL-BEING

Indicator overview

While Blair et al. (2021) consider SDG 3 to be only moderately correlated to the sustainability of bioenergy systems, a number of studies discuss the social benefits associated with improved human health that these systems can provide. The GBEP indicator list includes mortality and disease associated with indoor smoke associated with low-technology cookstoves (GBEP 2011). Others talk about particulate emissions, which are directly related to human health, and human toxicity, which is a combined measured used in life cycle assessment studies (de Souza et al. 2022). Within the context of the Sustainable Development Goals, these measures are most closely related to SDG 3, and can be tracked using the proposed SDG indicator *mortality rate attributed to household and ambient air pollution* (3.9.1) (UN Statistics Division 2022).

Key studies

Most often, SDG 3 is related to cooking and the challenges associated with combustion of biomass indoors. It is estimated that the use of cookstoves fueled by solid biomass (wood, agricultural residues, or livestock manure) lead to between 2-4 million early deaths per year (Semple et al. 2014, Rosenthal et al. 2018). Research suggests that simply improving the existing solid biomass stoves are not the best solution, and would only incrementally improve indoor air quality; better results are found with the use of biogas or ethanol, cleaner fuel products that can greatly improve efficiency and reduce particulate emissions (Rosenthal et al. 2018). Biogas technology has also been promoted by other authors as having particular application in home cooking, as a replacement for solid biomass fuels (Surendra et al. 2014). In China, biogas has been heavily taken up as an alternative to biomass fuels due to policies designed to improve indoor air quality (Gosens et al. 2013).

A study considered the use of bioenergy in cookstoves in Kenya, where the use of biomass for energy including cooking is predominant (Karanja, Gasparatos 2019). Because so much of the country relies on bioenergy, there is a substantive wood supply deficit for both firewood and charcoal. Four designs of stoves were considered, including improved biomass stoves, gasifying stoves, biogas stoves, and ethanol stoves. Shifting to more efficient stoves could dramatically reduce the amount of fuelwood required (in 2000, estimated at 741 kg/person/year); estimates suggest efficiency gains of 25-60% compared to conventional stoves. Benefits of adopting newer, cleaner-burning designs include reduction of indoor air pollution which in turn reduces the negative health impacts of smoke inhalation – including respiratory disease, pneumonia) (Karanja, Gasparatos 2019).

It is interesting to note that the introduction of biogas does not always lead to measurable impacts on medical expenses. In China, the use of biogas led to a small increase in household incomes, but did not reduce household medical expenses (Gosens et al. 2013). Similarly, a study in Africa that considered the introduction of better cookstoves found that the health benefit was very low, and provided a monetary value of less than 1% of all benefits being tracked in three countries (Senegal, The Gambia, and Guinea-Bissau) (Mazorra et al. 2020).

Another way of addressing human health concerns is to consider the human toxicity measure as reported through life cycle assessment, which gives a system-wide estimate of the risks associated with different practices. This approach was taken by de Souza et al. (2022), who compared the performance of sugarcane electricity to a number of other fossil-based and renewable electricity production pathways. Of all energy systems, oil had the worst aggregate result, while hydroelectricity had the best aggregate result, and bagasse electricity was in the bottom third of results. One strategy to improve the overall score of sugarcane electricity would be to reduce the amount of fertilizer utilized in sugarcane production.

Summary

This indicator is well tracked but currently limited in its use. In terms of indoor air quality, there is substantive literature showing progressive improvement as technology improves. Tracking progress related to this measure requires data describing (a) cookstove technology in use at the household or community level and (b) type of biofuel in use to power these systems. In particular, shifts to advanced solid fuel powered systems, and ultimately to biogas or liquid biofuel systems that burn cleaner and produce far fewer particulates, are desired. There is a paucity of literature that relates bioenergy systems to overall human health outside of the issue of indoor air quality. There is an opportunity to consider more holistic approaches which relate ecosystem services and overall health benefits to bioenergy production.

SDG 6 - CLEAN WATER AND SANITATION

Indicator overview

Access to clean water has been identified by stakeholders as a priority measure of bioenergy system sustainability (Martinez-Hernandez et al. 2024), as it represents a basic need. This is directly related to SDG 6, and can be measured as the *proportion of population using safely managed drinking water services* (6.1.1) (UN Statistics Division 2022).

Key studies

A selection of authors have identified strong connections between bioenergy development and water quality, particularly in terms of societal access to water resources (Diaz-Chavez et al. 2011, Martinez-Hernandez et al. 2024). Some literature suggests that expansion of grass crop cultivation for bioenergy production could actually reduce pollutants; for example, nutrient losses could be reduced between 21-94% with the growth of grasses, while sediment losses are reduced by 66-97%, and contaminants from 6-98% (Acharya, Blanco-Canqui 2018). Similarly, switching from corn to switchgrass production in the midwestern USA could reduce nitrogen loading in the watershed by 40% (Keerthi, Miller 2017), with better results seen in forested watersheds. De Souza et al. (2022) measured water depletion, freshwater eutrophication, and freshwater ecotoxicity to compare sugarcane electricity to other generation options. They found that sugarcane bagasse electricity does not deplete water but that it fares worse compared to wind (best result) due to the use of pesticides and fertilizers in production; the worst performing system was coal-fired electricity (de Souza et al. 2022).

Summary

This indicator is moderately well reported in the literature. The results suggest that bioenergy feedstock production could thus become an important component of a strategy to reduce water quality issues in certain locations, and that bioenergy landscapes can be designed to reduce impacts and improve water quality (Kreig et al. 2019). Key considerations to deliver these benefits include (a) an understanding of baseline water quality as related to reference land use scenarios (e.g. agriculture vs. forestry); and (b) quantitative measurement of key parameters such as nitrogen loading and runoff.

SDG 7 - AFFORDABLE AND CLEAN ENERGY

Indicator overview

The sustainability of bioenergy supply chains can be in part gauged by the ability of local populations to access bioenergy options, and the development of infrastructure and logistical support mechanisms to support bioenergy development (GBEP 2011, Burli et al. 2016). Within the SDG framework, this is most closely related to SDG 7 (Affordable and clean energy) and specifically two indicators: the *proportion of population with primary reliance on clean fuels and technology* (7.1.2) and *installed renewable energy-generating capacity in developing and developed countries*

(7.b.1) (UN Statistics Division 2022). These measures can be applied at both national and subnational levels, in order to track progress towards uptake and utilization of bioenergy options.

Key studies

While these indicators may be considered important measures of social sustainability, there is a paucity of data describing their performance over time. For example, a recent study examined biofuel use in Mali, but did not report on the actual proportion of households currently using sustainable bioenergy options (Segura-Rodríguez, Bhandari 2024). Other recent work in Africa summarizes the potential bioenergy output on the land but does not address household-level or community-level uptake (Röder et al. 2022).

The majority of studies reviewed in this work consider potential production level associated with bioenergy systems at local (Degani et al. 2022) regional (Singh 2015, Capaccioli et al. 2016, Parish et al. 2016, Xing et al. 2020, Parish et al. 2023) or national level (Simangunsong et al. 2017, Machado et al. 2021, de Souza et al. 2023). While these studies highlight potential outputs associated with different bioenergy feedstocks, and often reference these outputs to national energy needs, the linkage between bioenergy development and localized uptake is not always clear. More details on these studies can be found in the Environmental Measures section.

The importance of local-level uptake of bioenergy options has been highlighted over a number of different studies, including work in Africa (Ejigu 2008) and China (Jiang et al. 2020). Some work has also been done in developed countries, including the USA (Lindroos 2011) and Germany (Glasenapp et al. 2019). A recent study in rural Tanzania suggested that increased uptake of more efficient stoves, to 50% of households, would offset the impact of population growth on the need for biomass to cook (Hoffmann et al. 2018). Another study in Zambia examined the use of pellets and briquettes for cooking, and highlighted the cost challenges associated with increasing uptake at the local level (Kaoma, Gheewala 2021).

The value of investing in technology and logistics to support bioenergy has also been reported on; one study suggests that limited access to technology and infrastructure will hinder the ability of least developed countries across the global south to take up bioenergy options (Khatiwada et al. 2019). One useful study considered biogas production in Italy, and determined the drivers and conditions required to support biogas-to-bioelectricity production (Savio et al. 2022). Feedstocks under consideration were varied and included olive by-products, manure, and mixes of various biomass feedstocks. The production of bioelectricity in various regions were assessed and factors which may have supported its development were analyzed. Specific socio-economic parameters were not measured; instead, the study considered regions that were performing better or worse in terms of economic growth, population trends, etc., and then compared these regions to areas where bioelectricity had emerged in the country. Not surprisingly, this study found that regions with strong socio-economic performance had a better uptake of bioelectricity compared to regions that performed worse. This is particularly important because policy drivers in Italy were designed to move bioelectricity production across the entire country, but the actual regions able to take advantage of these policies tended to be places where resources (money or feedstocks) were already available. This finding suggests that policies need to be coordinated to reflect local conditions.

Summary

These indicators are poorly tracked and usually referred to in a qualitative or speculative way within the literature. The majority of studies undertaken that consider access to bioenergy do so at a national or regional level, reporting largely on the potential amounts of bioenergy (in the form of fuels, electricity, or heat) that can be generated and potentially added to the grid. Few existing studies are reporting on the barriers to localized uptake, which in turn makes it harder to track the benefits of bioenergy within the communities most directly involved in the supply chain. Achieving local benefit can be improved by focusing on three factors: (a) addressing cost at the household level, to ensure participation; (b) understanding the ability of ‘host’ regions or jurisdictions to support bioenergy uptake, as regions with existing resources are more likely to successfully implement these technologies; and (c) connecting both policies for both use and infrastructure development to local conditions.

SDG 11 - SUSTAINABLE CITIES AND COMMUNITIES

Indicator overview

One potential measure of bioenergy system sustainability is the ability of these systems to lead to a reduction in risk associated with cash crop production or forest operations, primarily due to the diversification of outputs off of the land base; this can in turn increase in the overall sustainability of local communities (Parish et al. 2016). This measure is most closely related to SDG 11, and can be approximated by measures of *the number of disruptions to basic services, attributed to disasters* (11.5.3) (UN Statistics Division 2022).

Key studies

A study in Tennessee, USA, suggested that switchgrass cultivation incurred a reduced risk of catastrophic disruptions relative to corn production (Parish et al. 2016). This may in part be due to the presence of a secondary revenue stream, particularly when switchgrass production is alternated with crop production; this can help to hedge against crop losses due to disasters, as the land may still produce biomass even if the cash crop is lost. Similar studies have examined the use of bioenergy thinning in slash pine plantations in the southeastern USA, finding that bioenergy thinning increased the value of the forest by about 11.5% by reducing risk associated with wildfires and pest outbreaks (Susaeta et al. 2009). In Canada, the use of precommercial thinning has been shown to help increase biomass supply in terms of total fibre harvest; moreover, mortality rates within thinned stands have been shown to have been reduced by as much as 50%, which could reduce risk associated with fire and pest outbreaks (Das Gupta et al. 2020).

The ability of bioenergy systems to contribute to community sustainability was also assessed by de Souza et al. (2022) through measures including photochemical oxidation, ozone formation, and bulk waste generation. This data was used to compare sugarcane electricity to a range of other fossil-based and renewable electricity generation options. The best performing technology was solar PV, while coal was the worst-performing technology, and bagasse electricity is ranked very close to wind and natural, gas, and hydro, and only slightly below solar PV.

Summary

This indicator is not well described in the literature. It is clear that diversification of biomass outputs can decrease risk, but additional work is needed to better understand the degree to which risk of catastrophe can be diminished. The impact that adding bioenergy outputs has on these systems is primarily related to (a) the number and value of outputs in the reference system (i.e., endogenous factors), and (b) the current level of risk of catastrophic failure from exogenous factors such as fire or pests. In the face of substantial wildfires across much of the globe, and increased pest outbreaks impacting both forestry and agriculture, this is a measure that should be explored in greater depth.

SDG 12 - RESPONSIBLE PRODUCTION AND CONSUMPTION

Indicator overview

There are a total of four indicators that have been proposed for bioenergy systems which are reflected in SDG 12. Two of the proposed indicators are very closely connected: the allocation and tenure of land used for biomass production, and trends in land use over time (van Dam et al. 2009, GBEP 2011, Burli et al. 2016). Within SDG 12, no indicators have been proposed that provide good proxies for these measures, although one could argue that the *proportion of agricultural area* *under productive and sustainable agriculture* (2.4.1) and *the forest area as a proportion of total land area* (15.1.1) (UN Statistics Division 2022), taken together and categorized to highlight land being used for biomass production for energy purposes, would provide a good substitute for these measures. A third proposed indicator is compliance with regulations, which can be further divided into compliance with rules around chemical use (fertilizers), biomass harvest and storage, and water use (Burli et al. 2016). This measure is approximated by the proposed SDG indicator on the *number of countries developing, adopting, or implementing policy instruments aimed at supporting the shift to sustainable consumption and production* (12.1.1) (UN Statistics Division 2022). A final, emerging indicator is integration of circular economy approaches into development of the bioenergy value chain (de Klerk et al. 2022), which can be approached using the *national recycling rate, tons of material recycled* (12.5.1) (UN Statistics Division 2022).

Key studies

In much of the developed world, bioenergy systems are being supplied via private land (typically agricultural land or small forest holdings) rather than publicly-owned areas. In this case, the allocation of land for bioenergy feedstock production is a decision taken by the landowners. Shivan and Mehmood (2010) explored the types of incentives that might induce landowners in the southeastern USA to take part in biomass production for energy purposes (Shivan, Mehmood 2010). A survey methodology garnered about 370 responses, the majority of whom (84%) stated that tax incentives would advance forest-based bioenergy. When presented with a range of policy options including more policy support for bioenergy, more support for producers, and more incentives at the pump, more than 60% of landowners viewed these policies as important. It was found that large landowners are less likely to support policy measures than those with smaller woodlots; this may be because larger landowners see bioenergy as competing with other land uses, such as timber production, and also suggests that these landowners might perceive returns from bioenergy as being low compared to returns for traditional forest products. Related studies suggest that landowners rely on strong timber pricing to support their decision to take part in the bioenergy market (Aguilar et al. 2014), and would be more likely to take part in supplying biomass if the price was high enough (Becker et al. 2013). Similar work was carried out in Virginia, where 900 forestowners were asked about the amount of forestland they would allocate at different values (Wolde et al. 2016). Interestingly, this study shows the importance of previous experiences of the landowner; those who had worked with the pulp and paper industry, for example, were less likely to be willing to allocate land to specific products as they have seen the consequences of locking in biomass growth to an industry where demand can disappear. Younger landowners, on the other hand, are more willing to take part in the bioenergy sector; in doing so, they respond to concerns about energy security, wildlife management needs, and overall level of knowledge about these systems (Joshi, Mehmood 2011).

The allocation of public lands for bioenergy systems has not been widely discussed in the literature. Some studies simply discount the utility of public lands for bioenergy feedstock production and concentrate instead on private land available (Van Deusen 2010, Merry et al. 2017). For publicly owned forests, a challenge identified is the public acceptability of bioenergy products and the willingness of society to utilize these resources for energy products (Stidham, Simon-Brown 2011). Existing laws may make it difficult to utilize forest biomass for energy purposes (Côté-Jinchereau et al. 2021). Other work has suggested that public lands can be a valuable asset in the production of feedstocks for energy or other bioproducts (Zappi et al. 2020). It is unclear, however, whether biomass producers are willing to engage with governments for the use of these lands. Studies examining the use of public land for grazing, for instance, shows that the willingness to pay rents for the use of these lands increases with awareness and experience, and that groups without prior experience are paradoxically less likely to engage with public land use (Mooney et al. 2019). Similar work on public forest lands suggest that society is more likely to embrace energy products if they are associated with clear benefits, such as reduced wildfire risk (Campbell et al. 2018). It should be noted that in the global south, the use of public lands as well as private lands is often implicit in the gathering of fuelwood or biomass for burning (Nansaior et al. 2013, Chisika et al. 2021). Bioenergy system development could reduce land conflicts; for example, a study in Kenya suggested that reducing overall biomass demand by improving technologies used in energy delivery could reduce conflicts over scarce resources and land, and reduce the chances of displacement due to low firewood availability (Karanja, Gasparatos 2019).

Very few studies have addressed the adherence of bioenergy systems to specific regulations, although it has been pointed out that bioenergy uses may in fact be discouraged by existing policies (Côté-Jinchereau et al. 2021), and that public acceptance of projects may in fact be increased by projects that demonstrate their adherence to local regulations through mechanisms such as certification (Lucier, Shepard 1997, de Man, German 2017, Mai-Moulin et al. 2019).

An emerging measure that might be used to address the use of materials in the bioenergy value chain is the adoption of circular economy approaches in bioenergy development. One study by de Souza et al. (2022) addressed this in part by using measures of ecological footprint, metal depletion, and hazardous waste; this data was used to compare sugarcane electricity to both fossil-based and renewable electricity options. When comparing these options, the worst aggregate result was received by solar photovoltaic systems, while the best aggregate result was found with hydro, followed closely by sugarcane electricity. In a study published in Australia, bioenergy, biochar, and cross-laminated timbers are highlighted as products that entrepreneurs are developing using wood waste (de Klerk et al. 2022). This study explored ways in which wood waste can be accessed, discussed benefits associated with recovering and reusing these wastes, and explored options for supporting entrepreneurs in this space. Finally, Mac Clay and Sellare considered ways in which the value chain needs to change in order to support a sustainable bioeconomy (Mac Clay, Sellare 2022). They primarily focus their argument on the ability of bio-based technologies can reduce GHG emissions while creating business opportunities. They suggest that risk can be lowered and benefits maximized by introducing shorter value chains with more vertical integration and coordination as well as increased recycling. There is currently no standardized approach to evaluating the circularity of a bioenergy value chain.

Summary

These indicators are poorly tracked, although a relatively large amount of data is available describing the role of, and incentives for, private landowners as suppliers of bioenergy. Less information is available on the use of public lands for bioenergy systems. Adherence to local laws is primarily addressed through studies of certification systems. The idea of circularity within bioenergy systems, while often referenced, is not well tracked and no common approach to evaluating this idea has yet been developed in the literature. Achieving responsible production and consumption patterns related to bioenergy systems should include (a) better understanding of the tradeoff in land use, (b) a clearer view on the role of private vs. public lands, (c) further exploration of the use of certification standards for bioenergy production and consumption, and (d) a focus on developing better means of tracking circularity in these systems.

SDG 17 - PARTNERSHIPS FOR THE GOALS

Indicator overview

Developing bioenergy systems requires building public support for the deployment and use of these systems, and thus public opinion and developing options for information sharing can be seen as important measures of sustainability (Parish et al. 2016). These measures are incorporated into SDG 17, and can be approximated by measuring *progress in multi-stakeholder development effectiveness monitoring frameworks that support the achievement of the sustainable development goals* (17.6.1) (UN Statistics Division 2022).

Key studies

In India, respondents to a survey pointed out the importance of public acceptability; while a strong majority of respondents agreed that bioenergy would create new jobs (91%) or benefit rural areas (89%), more than half of respondents (56%) suggested that low public acceptability would limit large-scale use of forest biomass for bioenergy (Halder et al. 2014). Similarly, a study in Tennessee, USA, suggested that switchgrass for energy enjoyed greater social acceptability due to positive public opinion when compared to corn production (Parish et al. 2016).

A study examining benefits between trading partners was carried out looking at wood pellet trade between the USA and Europe (Parish et al. 2018). This study suggests that trade can lead to mutually beneficial outcomes; the pellet market has created jobs in the USA while helping to meet policy goals in Europe. This study, while written at a high level, suggests that many of the issues which currently are raised in relation to trans-Atlantic pellet trade are not substantiated through analysis; for example, accusations that pellet production is leading to wholesale loss of hardwood forests in the USA cannot be supported through the data (Parish et al. 2018). This work emphasizes the importance of outreach and engagement with the public in order to avoid negative outcomes.

Determining public opinion can be aided by introducing aspects of cost. For example, one study in China examined the use of straw as a feedstock for bioenergy, and specifically asked questions about how farmers made decisions to enter this value chain (Del Valle et al. 2022). Importantly, policies that can help offset the costs of straw recovery are seen as critical, as this increases utilization rates for straw. Public awareness and specifically educational programs designed to help farmers understand the value of straw in local markets were seen as critical. Similarly, it has been shown that users may be willing to pay more for clean energy, particularly when the benefits (decreasing wildfires, reducing pest outbreaks, etc.) are clearly communicated to users; a study in the USA found that consumers would pay around $0.049/kWh (about $40.50/person/year) for wood-based bioelectricity when these benefits are understood (Susaeta et al. 2011).

Finally, recent work has highlighted the importance of communicating benefits at the individual stakeholder level, which is particularly important in driving farmers to uptake crop production; this work also highlights the importance of small-scale demonstration facilities to drive development of feedstock supply chains (Yang et al. 2022).

Summary

This indicator is moderately well explored in the literature. The sustainability of bioenergy systems does in part rely upon public support for these systems, which requires clear communication strategies. The most successful systems rely on (a) a well informed public who understand the reasons why bioenergy systems are being deployed, and (b) an idea of the value that these systems can bring in relation to the status quo.

KEY TAKEAWAYS

This review addressed ten potential indicators for the social sustainability of bioenergy systems. Of these, two are well covered in the literature. The impact of bioenergy on food systems is a factor that has been of considerable concern since bioenergy was first introduced and thus is well developed; there is some consistency in the ways that this indicator is measured and some consistency in the findings. The potential of bioenergy options to improve human health is also well explored in the context of clean biofuels for indoor cooking and heating; this primarily has application in the global south, where cookstoves are a major consideration. The ability of bioenergy to improve human health in other systems is not well explored.

Four additional indicators were moderately well covered in the literature. (1) The first is access to clean water, which can be related back to bioenergy system implementation and is addressed in an increasing number of studies. The key finding is that bioenergy systems, particularly non-food biomass, can be used to clean up runoff by absorbing excess nutrients before they enter the water supply. This work highlights the need to consider bioenergy as a component in forestry and agricultural production systems. (2-3) Of the four indicators that are linked to responsible production and consumption of bioenergy, two are moderately well explored – those of land allocation and land tenure. However, these issues are mostly addressed in the literature by the willingness of landowners in various parts of the world to take part in the bioenergy supply chain; the work primarily focuses on private lands, while the growth of biomass on public lands is not widely discussed or monitored. (4) Finally, public opinion and flow of information is moderately well covered in the literature, and studies exist that provide guidance on how to best convey the impacts of bioenergy systems to broader public.

It is more difficult to assess the four other indicators considered. (1) The accessibility (or uptake) of bioenergy within local populations is not well tracked, as for the most part studies have focused at the national or (at best) regional level, and little data is available which describes the uptake of bioenergy at local or community levels. (2) The adherence of bioenergy systems to local regulations is mostly limited to assessments of certification methodologies, which act as a check on the legality of biomass and bioenergy production systems. (3) The ability of bioenergy systems to be part of a circular economy is also not well assessed in the literature to date, although authors have pointed out potential. (4) Risk of catastrophe, which speaks to the sustainable communities, is also not well covered in the literature.

The social data available on bioenergy system impacts are limited and do not provide a 'holistic' view based on the definition of social sustainability found in the SDGs, or based on the indicators suggested through GBEP. Moving forward, key priorities should be (a) to develop more consistent methodologies to measure the responsible production and consumption of bioenergy, which addresses land allocation and the sustainable use of materials; (b) to develop consistent approaches to track the accessibility of bioenergy to local populations; and (c) to review methods used to determine system boundaries, as appropriate use of these boundaries will help place bioenergy into the context of existing forestry and agricultural systems and lead to better understanding of trade-offs between different land uses.

Section 2 - Economic Measures

A summary of economic measures can be seen in Table 2. The SDGs related to each proposed indicator are identified. In Column A, an Asterix (*) indicates that attendees at the 17 September 2024 workshop suggested that this indicator was of particular importance. In Column B, the SDGs are categorized by the clusters identified by Blair et al. (2021), with high (H), moderate (M), and low (L) correlation to bioenergy supply chain sustainability.

Table 2 - Measures of economic sustainability in bioenergy systems

A	B	SDG	Indicator	Selected literature
	M	1 NO POVERTY	Trends in land prices compared with previous trends	Burli et al. 2016; Machado et al. 2021
	L	4 QUALITY EDUCATION	Training and requalification of workforce	de Souza et al. 2022; GBEP 2011; Martinez-Hernandez et al. 2024
	L	5 GENDER EQUALITY	Unpaid time spent collecting biomass	GBEP 2011; Martinez-Hernandez et al. 2024
*	H	7 AFFORDABLE AND CLEAN ENERGY	(1) Access to modernized energy; (2) Energy cost; (3) Energy price volatility	GBEP 2011; Martinez-Hernandez et al. 2024; Parish et al. 2018
	H	8 DECENT WORK AND ECONOMIC GROWTH	(1) Economic productivity (gross value added, profit per unit area); (2) Trends in per capita income; (3) Direct jobs, indirect jobs, trends in jobs and income by gender; (4) Trends in work hours	Burli et al. 2016; de Souza et al. 2022, 2023; GBEP 2011; Machado et al. 2021; Martinez-Hernandez et al. 2024; Obidzinski et al. 2012; Parish et al. 2018; Song et al. 2015a; Song et al. 2015b; Wang et al. 2018; Xing et al. 2020
*	H	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	(1) Financial viability of projects; (2) Cost of CO_2 abatement; (3) Investments in research and development	Akter et al. 2024; de Souza et al. 2022; Lim et al. 2023; Perdue et al. 2017
*	M	10 REDUCED INEQUALITIES	Community benefit	Burli et al. 2016; Obidzinski et al. 2012

SDG 1 - NO POVERTY

Indicator overview

A concern around bioenergy supply chain development is the impact that this sector might have on land prices, and the ability of local populations to be able to access and hold the land (Burli et al. 2016, Machado et al. 2021). Access to land falls under SDG 1, and can be approximated using the recommended indicator of the *proportion of total adult population with secure tenure rights to land… by sex and type of tenure* (1.4.2) (UN Statistics Division 2022).

Key studies

One concern related to the development of bioenergy systems is that this would lead to increased demand for land, which in turn would push small landowners or leaseholders off of the land in favour of large corporations entering this space. This concern is not always supported by the literature. An analysis of socio-economic impacts related to bioenergy production was carried out in Argentina and examined soybean and switchgrass production on agricultural cropland, degraded grasslands, and non-degraded grasslands (van Dam et al. 2009). To examine economic impacts, they considered land prices and the prices of food and feed. While findings were preliminary, the study found that soybean production, which focused more on cropland, was more likely to increase prices, while switchgrass was more likely to be associated with decreased prices as the crop can be grown on a much wider basis. Similarly, a study in India looked at 415 households to understand socio-economic benefits associated with growing biofuels crops (Patel et al. 2021); only 38% of households felt that using bamboo for biofuel would affect land security.

In contrast, Obidzinski et al. (2012) point out that bioenergy development can lead to challenges for landholders at the lower end of the economic spectrum. In a study examining oil palm development to support biodiesel production, they reported on the divide between households able to raise initial capital to invest in oil palm plantations, and highlighted that more established oil palm plantations yielded stronger benefits (Obidzinski et al. 2012). They also pointed out that oil palm plantations come at high environmental costs as the land cleared to establish these plantations is typically primary or secondary forest delivering strong benefits. Other landowners in the area can be negatively impacted as the investment in bioenergy crops can be funneled through elites – early adopters or individuals with strong connections. This paper also points out the exaggerated reports of benefits that are often delivered by companies with an interest in these crops.

In a study looking at bioeconomy development in Brazil, land use change was largely tilted towards growth the area under agricultural crop production. Within bioeconomy scenarios, overall land use change was limited based on Brazil's GHG emission reduction targets. Because this was a national-level study, substantive growth in agricultural production was anticipated, which could lead to increased demand for land and thus increased pricing (Machado et al. 2021).

Not all studies have addressed SDG 1 in the same way. A study in Brazil looked at the ability of bioenergy deployment to meet sustainable development goals (SDGs), specifically considering the use of sugarcane bagasse in producing electricity (de Souza et al. 2022). For SDG 1, they considered average annual wages and employment #s per GWh – measures that are not actually associated with the indicators recommended by the UN.

Summary

This indicator is not well tracked. There are contradictory studies in place, suggesting that local context may play a dominant role in determining whether or not landowners will be able to take part in the bioenergy sector. To better understand this measure, more consistent data on (a) land ownership trends, and (b) land prices would be necessary.

SDG 4 - QUALITY EDUCATION

Indicator overview

One potential measure of bioenergy system sustainability is the boost that a successful sector will give to training (GBEP 2011, de Souza et al. 2023). This measure is a component of SDG 4, and can be approximated using the recommended indicator on *completion rate (primary education, lower secondary education, upper secondary education)* (4.1.2) (UN Statistics Division 2022).

Key studies

In some cases, bioenergy development will spur the demand for highly-trained workers. This can include employment in areas such as engineering systems, computers, economics, international trade, forest managers, biologists and engineers; further, bioenergy from renewable resources has an employment rate much higher than other renewables, and also has a lower investment cost for job creation (Vogt et al. 2005). This is countered by other studies, however. For example, de Souza et al. (2022) found that sugarcane bagasse electricity ranks lower than other renewable and fossil-based electricity options due to the heavy use of agricultural workers, who in Brazil typically have less training than people in the energy sector; average education was 9 years for switchgrass bagasse electricity, compared to an average of 12 years for hydro and similarly high scores for other energy options. At least one study found that adding the costs of education on a per child basis could increase the cost of bioenergy systems, by 4% in Brazil and 3% in Ukraine (Smeets, Faaij 2010).

Summary

This indicator is not well tracked. It does seem clear that the level of training that will be achieved is likely related to two factors: (a) the level of bioenergy technology being implemented, and (b) the infrastructure for education and development present in the region being considered.

SDG 5 - GENDER EQUALITY

Indicator overview

One of the potential impacts of bioenergy development are changes to traditional, gendered roles, particularly around the collection and use of biomass for cooking and heating (GBEP 2011, Martinez-Hernandez et al. 2024). This impact is best captured within SDG 5, and can be approximated using the proposed indicator of *proportion of time spent on unpaid domestic and care work, by sex, age, and location* (5.4.1) (UN Statistics Division 2022).

Key studies

Research suggests that adoption of better bioenergy technologies (i.e., advanced cookstoves running on liquid or gaseous biofuels) would lead to substantive outcomes in the global south. A recent study in Kenya suggests that introducing better cookstoves could significantly decrease the labour requirement for girls and women, on whom the burden of firewood collection is high, would be reduced, which would in turn create opportunities including better school attendance for children (Karanja, Gasparatos 2019). Work suggests that individual households with better cookstoves could reduce firewood consumption by between 186-763 kg/year (Uwizeyimana et al. 2024). One study suggests that generating biogas using animal manure could dramatically impact firewood and kerosene use in cooking; they found that up to 5,818 PJ/year of biogas could be generated across the global south from various livestock, and that this would be equivalent to about 727 million t/year of firewood and 41.6 billion litres/year of kerosene (Surendra et al. 2014). At the consumption rates previously reported, this would potentially impact between 953,000 and 3.9 million households per year depending on fuelwood use.

Studies in Africa looked at the labour requirement for gathering firewood, cooking, and tending crops. On report highlighted the fact that improved cookstoves can deliver additional time savings which can be given a monetary value, along with the value of avoided medical costs and a carbon credit value; overall, the study suggested economic benefits of between 159-319 € in Senegal, 145-345 € in The Gambia, and 97-193 € in Guinea-Bissau (Mazorra et al. 2020). A second study posited that time savings associated with gathering fuelwood could be reallocated to tending crops; because women collect the majority of fuel, it was found that simply shifting 10% of time away from fuel collection to crop cultivation could mean that a female-led household could match male-led households in crop outputs (Villamor 2023). The savings in time related to fuel gathering and cooking can thus be considered a gender co-benefit, although the introduction of better cookstoves could simply lead to a shift in labour for women to other tasks, rather than an overall reduction in work (Villamor 2023).

In China, the introduction of biogas as a fuel for household cooking and heating has substantively reduced the workload associated with fuel collection. Prior to the introduction of biogas systems, the number of days involved in fuel collection ranged from 9.8 (Guangxi) to 13.7 (Hubei) to 18.5 (Gansu); after the introduction of biogas, the number of days ranged from 8.2 (Guangxi) to 6.6 (Hubei) to 14.8 (Gansu), reductions of 17%, 52%, and 20% respectively (Gosens et al. 2013). It should be noted that biogas systems are expensive and do not pay for themselves; the subsidy provided by the Chinese government is essential to ensure uptake of these systems. Similarly, in an examination of biogas plants in Bangladesh, respondents highlighted the impact of biogas plants on the workload of women, and suggested a significant time savings related to gathering wood (average of 42 min) and cleaning equipment (average of 28 min per household per day) (Rahman et al. 2019).

While household benefits can be substantial as bioenergy options are employed, regional economic development may not deliver the same gender benefits. De Souza et al. (2022) compared employment by gender in sugarcane electricity to a number of other generation options, including fossil-based and renewable systems. They found that very few women are engaged in the sugarcane electricity sector (23%), which was lower than other renewable energy options.

Summary

This indicator is well tracked with relation to household roles, particularly in the global south; it is not well developed when it comes to gender roles in the bioenergy sector at large. There are several key considerations, including (a) the nature of the bioenergy system being employed and the nature of the system it replaces, and (b) the current division of labour within households, by gender. Significant data on gendered roles in employment may be found through other measures, as discussed previously.

SDG 7 - CLEAN AND AFFORDABLE ENERGY

Indicator overview

One way to evaluate the sustainability of bioenergy systems is to explore the ability of populations (at various scales) to access bioenergy options, and to understand basic cost and price volatility associated with these options (GBEP 2011, Parish et al. 2018). This can in part be evaluated using data describing SDG 7, specifically the *proportion of population with primary reliance on clean fuels and technology* (7.1.2) (UN Statistics Division 2022). Note that within the suggested indicator list developed for the SDGs, energy pricing is not included; however, understanding the cost of bioenergy as referenced to current systems is an important component of bioenergy system sustainability.

Key studies

It is clear that the cost of wood energy is closely related to the cost of harvest and recovery of woody feedstocks, and this is relatively well explored in the literature. In systems where biomass is recovered from wood processing facilities (i.e. chips, sawdust) the feedstock cost is correspondingly low. In systems that rely on purpose-grown trees or crops, the harvest and extraction costs need to be assessed. In Australia, the marginal cost of wood for energy was approximately AU$10.2/$m^3$, of which 30% was associated with harvest and 70% was associated with extraction; this is about double the cost of sawlogs in a similar system (Ghaffariyan et al. 2015). In these systems, biomass recovery for energy reached 37 green metric tonnes/ha, providing about AU$1,110/ha in additional income for growers. It is interesting to note that the amount of biomass that can be processed varies on a per machine hour (PMH_0) basis, ranging from 97.3 green metric tonnes/ PMH_0 for a feller buncher used to collect biomass, 60.2 t/ PMH_0 for a mobile chipper used to chip in situ, 57.8 t/ PMH_0 for a flail, and 57.3 t/ PMH_0 for transport (Ghaffariyan et al. 2013); it is suggested that collecting biomass and chipping at a central location is more productive than using mobile chipping systems (Ghaffariyan et al. 2012). Chipping at the roadside is highly productive, delivering biomass recover of between 10-29 green t/ha, and income of AU$300-870/ha for producers (Ghaffariyan et al. 2012).

Many studies exist which estimate the costs of delivering bioenergy into a grid. Breakeven costs are generally closely related to the existing systems into which bioenergy is being added, and thus are difficult to compare. Studies give a range of values; for example, miscanthus and switchgrass were shown to have breakeven costs of between US$44-80/t (dry matter) for electricity production, which was between 2-4x greater than the reference coal-based system (Khanna et al. 2008). In Finland, the cost of bioenergy using heat containers was comparable to direct heating with oil, but not competitive with existing district heating systems (Kc et al. 2021). In Canada, the greatest driver of biomass energy feedstock costs may be the size of the tree, as larger trees can be harvested in a whole-tree fashion and provide a mix of lumber as well as pulp and potentially energy at little additional cost; smaller trees provide fewer residues, and thus more trees must be recovered at higher costs to support bioenergy production (Canuel et al. 2022). Bioenergy has thus typically been most widely used where subsidy is available, where the reference system costs are similar to the costs for developing bioenergy options.

There are different strategies for reducing the cost of bioenergy options. For example, delivering high-value products in combination with lower-value energy products is a strategy that is widely explored in the literature (Mabee et al. 2004, Vogt et al. 2005). Bioenergy options can also be used to improve the cost efficiency of microgrids that are primarily operating from wind and solar power, which increases the potential value of the bioenergy output and makes it more attractive for utility customers. Bioenergy options are dispatchable and can be deployed at a relatively small scale, making them useful and possibly more cost-effective than natural gas when both heat and power needs are considered (Zheng et al. 2018).

One barrier to the uptake of new technologies is capital cost; for example, managers of existing district energy systems may seek to use biomass in the present-day plant rather than investing in expensive, and complicated, pyrolysis or gasification systems, even though these systems may be more efficient (Akhtari et al. 2014). One approach might be to embrace co-firing options, that utilize biomass with coal or other fossil fuels, rather than new or stand-alone facilities. This finding is born out by other studies, which find that carbon abatement costs are up to six times higher with new technologies compared to utilizing simple combined heat and power facilities (Blair, Mabee 2020). Costs are expected to decrease as scale of the plant rises, as shown in a similar study in Canada (Upadhyay et al. 2012).

While much of the literature focuses on the costs of producing feedstock or generating bioenergy, there is less data describing the consumer cost. One study describes the uptake of biogas as a fuel for cooking and heating has led to improvements in household income in rural China, with improvements in household income ranging between 0.7% and 3.8% after the introduction of household biogas systems (Gosens et al. 2013).

Summary

This indicator is not well tracked, largely because it is so dependent upon the conditions at the time and place of the study. Bioenergy options can be attractive but generally require subsidy to be competitive with existing energy sources. To achieve benefits in this space, bioenergy options must (a) target higher-cost energy sources or niche applications which are not well served by existing energy options, and (b) synergize with other components of the energy system (e.g., provide dispatchable backup power or heat). Subsidy for infrastructure development and/or consumer use is likely required.

SDG 8 - DECENT WORK AND ECONOMIC GROWTH

Indicator overview

The sustainability of bioenergy feedstock supply chains can be in part measured by their ability to add to the overall economic performance of a region (small or large) or country, while providing good jobs for people within this area (GBEP 2011, Burli et al. 2016, de Souza et al. 2023). These measures are incorporated within SDG 8. Economic growth is captured by two recommended indicators within this goal, a*nnual growth rate of real GDP per capita* (8.1.1), and a*nnual growth rate of real GDP per employed person* (8.2.1) (UN Statistics Division 2022). Employment is captured through two additional indicators recommended within this goal, the *average hourly earnings of employees, by sex, age, occupation and persons with disabilities* (8.5.1) and *Unemployment rate by sex, gender, and persons with disabilities* (8.5.2) (UN Statistics Division 2022). Finally, a number of authors have suggested that illness, injury, and fatalities associated with the bioenergy supply chain should be tracked as an indicator of overall system sustainability (GBEP 2011, Martinez-Hernandez et al. 2024). This measure is most closely approximated by the *fatal and non-fatal occupational injuries per 100,000 workers, by sex and migrant status* (8.8.1) (UN Statistics Division 2022). It should be noted that while these measures are grouped under SDG 8, they provide important measures of gender-based employment and income which address other goals of equity and diversity within the SDGs.

Key studies

Economic performance

Biomass can be transformed into energy and fuel products that can substitute for natural gas, gasoline, diesel fuel, or jet fuel, as well as converted into electricity. There can be substantive differences in the costs associated with these energy sources and with the cost of creating a bio-based substitute, and thus understanding the reference system being used is key to assessing economic impacts associated with bioenergy pathways.

There are good examples of projects that have used reference pathways to show bioenergy systems that deliver positive socioeconomic benefits. For example, the Eno Energy Cooperative in Finland is owned by 54 members and operates three district heating plants, delivering a total of 15,400 MWh of energy (heat) and using 27,000 m^3 of wood chips per year (Lehtonen, Okkonen 2019). This heat supports homes, a seniors centre, community centres, schools, a fire station, a bank, and a health care centre in the local communities. Between 2000-2015, this project has provided total benefits of € 13.94 million to the local economy, including investments of € 5.35 million into forestry operations and € 3.75 million into upgrades to local utilities, coupled with savings related to reduced heating costs of € 2.28 million in households and € 1.80 in public buildings in the municipality. Note that there is a strong interdependence between the price of heating oil and the savings received over this period; if the cost of heating oil is high, the relative savings associated with the bioenergy system increase, but when costs are low, the relative benefits of bioenergy can decrease or disappear.

In Greece, a study considered the use of winery waste (pomace) as a feedstock for an extraction- and pyrolysis-based biorefining process (Zabaniotou et al. 2018). In this analysis, an average of 15 t/ha of grapes were harvested, yielding about 2.83 t/ha in pomace, which in turn could yield hydrocolloids, grapeseed oil, char, biooil, and biogas. This study suggested that the economic benefit to the producer of the combined biorefinery products would be in the range of 6980€/ha, compared to the value of the wine of 210000€/ha.

Most studies carried out in this space try to estimate impacts associated with bioenergy without much discussion of the existing or reference system; these studies tend to provide very positive outlooks on bioenergy performance. In British Columbia, Canada, researchers found that using harvest residues and wood processing residues in the Williams Lake Timber Supply Area could support a 5 MW cogeneration plant (producing heat and electricity), a 0.5 MW electricity only plant, a 400 dry tonne/day pyrolysis plant, a 2 MW heating plant, and a 15,000 tonne per year pellet plant. Operating these facilities could generate a net present value of between C$330-550 million, as well as between 82 and 239 jobs (Cambero, Sowlati 2016). Similarly, a study in Brazil examining the integration of bioenergy crop production and livestock management suggested that the production of 89 billion litres of ethanol per year could generate $15 billion per year in profit (de Souza et al. 2023). The use of straw for regional energy production in Jilin Province, China was assessed (Wang et al. 2018). By 2030, 47.1 Mt of straw biomass could be available on an annual basis; converting this material to energy through direct-combustion, briquette fuels, and cellulosic ethanol could result in a net profit of $US 2.2 billion. Finally, a study in Indonesia suggested that in 2013, up to 132 PJ of wood could be recovered from combined harvest residues (3.7 Mt/year) and wood processing residues 3.6 Mt/year), providing an economic value of about US$5.6/t, this value being the discounted profit after wood residue costs and transformation costs are set against the selling price of about US$135/t (Simangunsong et al. 2017).

Some work has been done to understand the differences between strategies that focus on local benefits as opposed to regional or international benefits. In the USA, Saul et al. (2018) examined the use of logging residues and small-diameter trees (about 181,450 dry tonnes per year) to generate both biochar and liquid biofuels, the latter of which was to be used in local applications. This was compared to a regional strategy that saw 635,000 dry tonnes/year of residues collected for biojet production, and an international model that would see 272,150 dry tonnes/year converted to pellets for international trade (Saul et al. 2018). Unfortunately, in this study the only currently viable technology is that of pellet production, so the scenario which was deemed most likely was the international development scenario. It should be noted that a regional strategy (producing biojet) was far more successful at generating economic activity compared to a localized strategy or an international strategy. The contribution to gross regional product was estimated to be $110/t in the local strategy, compared to $239/t in the regional strategy, and $80/t in the international strategy (Saul et al. 2018). This work suggests that prioritizing local benefit might not lead to the most productive system.

It should be noted that ensuring minimum wages can add significant costs to bioenergy systems; one study suggested that biomass costs could increase by up to 24% in Brazil, and 6% in Ukraine, if minimum wage standards were applied to all workers within the supply chain (Smeets, Faaij 2010). In countries without health care benefits, additional costs for this should also be considered; in the case of Brazil, this can add about 3% to the cost of bioenergy, while in Ukraine, this works out to be a 1% increase (Smeets, Faaij 2010).

Very few studies provide a holistic view of economic development across a region or nation; usually, estimates of GDP growth are restricted to sector-based development and do not consider trade-offs with other sectors. In a study looking at sugarcane, soybean, and forest biomass development in Brazil, it was found that overall GDP growth would drop under bioeconomy scenarios by between 0.17-0.75% compared to a business-as-usual case, but note that total GDP growth was expected to be 53.9% over the same period. Subsidies required by the bioeconomy are

175-265% higher than in the business-as-usual case but represent a very small proportion of investments expected in each scenario (about 0.35%). The total investments would reduce by 3.6-7.2% compared to BAU (Machado et al. 2021). By comparison, increasing bioenergy utilization in China was considered using an input-output modeling approach (Song et al. 2015a, Song et al. 2015b). This work found substantive greenhouse gas emission reductions as well as improved GHG intensity, with substantial increases in the proportion of renewable energy utilized in each bioenergy scenario considered. In an optimal scenario, a gross regional product growth rate of 8.41% can be achieved by 2025. All scenarios were subject to an increasing carbon tax; in scenarios producing bioelectricity, an additional subsidy needed to be provided to ensure production, while in a scenario looking at solid fuel production, no subsidy was required. Thus it is important to consider overall economic impacts to understand the actual impact of bioenergy systems.

Finally, de Souza et al. (2022) measured work accident occurrences and share of workers at minimum wage in order to compare sugarcane bagasse-based electricity systems to other fossil-based and renewable electricity generation options. The best performing technology was hydro and the worst was oil; bagasse electricity scores lower due to the number of work-related accidents and the higher number of underpaid workers in the agricultural sector.

Numbers of jobs

Some studies are highly localized and provide a good estimate of direct and indirect employment. The Eno Energy Cooperative in Finland was reported to have created approximately 76 jobs between 2000 and 2015 (Lehtonen, Okkonen 2019). Of these, about half (39) are related to forestry. Approximately 73 additional jobs are created through the savings generated by the project, which include new jobs in retail trade (33), health (16), and education (5). Over this period, total income impacts are approximately € 6.71 million, of which € 3.43 million comes from heat generation, and € 2.79 million comes from savings. Similarly, in British Columbia, Canada, researchers found that using harvest residues and wood processing residues in one timber supply area could support a combination of cogeneration, heat, and electricity plants, as well as a pyrolysis plant and a large pellet facility. Operating these facilities could generate between 82 and 239 jobs (Cambero, Sowlati 2016). Studies in Australia suggested that about 15 jobs could be created through the collection of 200,000 tonnes of wood waste (Ghaffariyan et al. 2012, Ghaffariyan et al. 2015), or about one job for every 13,300 tonnes of wood waste collected. Other analyses in the USA suggest that a localized bioenergy strategy that sees the development of biomass depots could result in up to 18.75 full-time job equivalents per depot, handling a total of 68,000 bone-dry tonnes per year; this is equivalent to about 1 job for every 3,600 tonnes of biomass per year (Crandall et al. 2017). Finally, in examining switchgrass and soybean production in Argentina, data on employment suggested that some bioenergy feedstock pathways, particularly those related to switchgrass production, could lead to significant additional jobs, but the authors cautioned that more data is required to better understand these relationships (van Dam et al. 2009). It was estimated that the soybean bioenergy chain could produce between 58 and 312 jobs per year, depending on the scenario considered (equivalent to 1 job for every 330-2500 t of biodiesel generated); the switchgrass bioenergy chain could produce 1,500-12,600 jobs per year (equivalent to one job for every 660-1000 tonnes of pellets produced).

By comparison, many studies have been carried out which provide less detailed estimates of job creation across a large region and/or extended period of time. For example, a study in Jilin Province, China, examining straw availability for regional energy production (Wang et al. 2018). This work suggests that by 2030, 47.1 Mt of straw biomass could be available on an annual basis, discounting a portion of straw left on the field for environmental purposes or utilized for existing agricultural purposes. It is estimated that the use of this biomass in a variety of energy operations could create up to 166,000 jobs (direct and indirect). Other studies provide a much more generic assessment of employment benefits. A study examining switchgrass production in Tennessee, USA, suggested that switchgrass systems had higher social sustainability than conventional corn systems, and would deliver additional jobs, increased household income, and improved local livelihoods relative to corn-based systems (Parish et al. 2016). However, the results were not quantified and thus are difficult to compare to other studies.

It would seem that the geographic level at which bioenergy strategies are focused could affect employment, with localized strategies not always creating the greatest number of jobs. This is an example of where trade-offs exist between economic sustainability and social benefits. For example, employment related to various bioenergy scenarios was considered by Saul et al. (2018), who looked at local, regional, and international development pathways. This study found that at the local level, 1 job was created for every 605 tonnes of feedstock used, compared to 1 job for every 265 tonnes in the regional strategy and 1 job for every 670 tonne in the international strategy (Saul et al. 2018).

It is important to track the impacts of bioenergy development within the entire economy. In a study looking at sugarcane, soybean, and forest biomass in Brazil, bioeconomy scenarios results in a higher unemployment rate compared to a business as usual case, rising from about 3.87% to 3.92-3.95%. This reflects the fact that while the number of jobs in the bioeconomy sector increases, there is a corresponding decrease in jobs in the fossil sector, and another decrease that is associated with a drop in GDP and government investment (Machado et al. 2021). Very few studies are available that track these tradeoffs.

It is also important to understand local conditions in developing bioenergy projects. A cautionary tale can be found in Yucatan, Mexico, where the development of jatropha plantations for bioenergy did lead to some (unquantified) local jobs over the short term. In a series of semi-structured interviews, 72% of respondents suggested that the jatropha plantations were good for their community (Banerjee et al. 2017). Of workers who took part in the interviews, about half of respondents felt that they were paid fairly for their work, while 34% of respondents disagreed. Unfortunately, all of the plantations closed after 3 years of operation due to low productivity. This has left most of those who had been employed once again jobless, and had very limited long-term community benefit.

Finally, some studies have compared employment in bioenergy supply chains to other renewable energy options. One such study, considering electricity from sugarcane, found that bioenergy had the lowest annual wages of all electricity options (although still substantively above minimum wage); 2.5-2.6 employees were utilized per GWh for sugarcane electricity, far above hydro (0.42/GWh) and wind (0.39/GWh) (de Souza et al. 2022).

Summary

This indicator is well tracked and there are a number of relevant, useful studies available. Because the impact of bioenergy systems is so dependent upon context, it is difficult to compare these studies. The economic impact and jobs associated with bioenergy projects must be measured in relation to reference systems, and to local conditions. It is clear that measurement of these impacts should include (a) clear definition of system boundaries and (b) a detailed explanation of reference or baseline conditions. In ideal cases, evaluating these impacts would an exploration of both sectoral impacts and trade-offs within other sectors. It should be noted that while many studies are available, there is a large gap in terms of understanding gendered roles, although this is data that could be tracked in the context of employment and wages.

SDG 9 - INDUSTRY, INNOVATION AND INFRASTRUCTURE

Indicator overview

One important measure, identified in the September 2024 workshop, is the financial viability of individual projects. While this is not well captured within the SDGs, useful measures include

Proportion of small-scale industries in total industry value added (9.3.1) and *Proportion of medium and high-tech industry value added in total value added* (9.b.1), both of which speak to the success of bioenergy businesses (including emerging industry, as well as industry utilizing high-tech approaches to bioenergy production) in contributing to overall economic outputs (UN Statistics Division 2022).

Another important measure identified at the September 2024 workshop is the cost of CO_2 mitigation. This is reflected within SDG 9 as *CO_2 emission per unit of value added* (9.4.1). Finally, a measure of overall bioenergy supply chain sustainability may be the investment in research and development (R&D) to support these systems (de Souza et al. 2022). This measure is captured within SDG 9, and specifically by the proposed indicator of *research and development expenditure as a proportion of GDP* (9.5.1) (UN Statistics Division 2022).

Key studies

A number of studies have considered the economic viability of bioenergy projects. Some have focused on feedstock production systems such as short-rotation pine in the USA (Perdue et al. 2017), various tropical wood species in west Africa (Akoto et al. 2020), or the use of agricultural residues and crops (Akter et al. 2024). Other studies have looked at cropping systems on marginal lands (Fahd et al. 2012), specifically considering the lower land value and ability of different crops to provide returns in places where conventional agriculture is not feasible. There are also a wide range of studies which consider individual plant development using a variety of technologies, including biogas generation (Belinska et al. 2024), cofiring biomass and coal (Hoffmann et al. 2012), production of liquid biofuels (Zarrinbakhsh et al. 2014), and emerging biorefinery approaches (Abu-Omar et al. 2021, Manhongo et al. 2021). These studies primarily take an econometric or techno-economic analysis approach to evaluating individual project costs; as might be expected, individual project costs and the viability of these projects are highly dependent upon local conditions and vary substantively through the literature.

A selection of studies are also available on the cost of CO_2 abatement, or the unit cost of reducing carbon dioxide emissions. One recent study examining a waste-to-energy system that incorporated carbon capture and storage systems, finding that the levelized cost of carbon abatement ranged between US$89-184/t CO_2-equivalent depending upon the energy source for which bioenergy was substituted (Lim et al. 2023). A study in Canada found that the cost of substituting bioenergy for fossil energy would exceed C$300/t CO_2-e (about US$215/t CO_2-e) (Wang et al. 2020). Some work has suggested that forest carbon sequestration may be a lower-cost abatement approach than bioenergy recovery (Vass, Elofsson 2016). It should be noted that the cost of mitigation is highly dependent upon study design (i.e., system boundaries) as well as the reference energy system under consideration, which makes these costs difficult to compare.

The literature does not include many examples of reviews of R&D investment into bioenergy supply chains, although studies have highlighted a number of needs associated with this sector, including a range of technical challenges which still need to be overcome to improve the overall competitiveness of the sector (Masse et al. 2015). One of the few examples considered trends in research related to the use of bio-waste and the circular economy, and highlighted the role of research in developing the microbial bioconversion processes that has made recovery and reuse of a wide range of bio-waste streams possible (Jain et al. 2022). The emergence of new tools, such as Artificial Intelligence, and their applicability to bioenergy development has been highlighted in recent work (Jha et al. 2017). Researchers who have worked in this space point out that for a number of new technologies, developing countries may not have the capacity or research infrastructure required to engage; for example, research into algae as a potential biomass substrate is limited to countries with well-developed capacity (Adenle et al. 2013). De Souza et al. (2022) addressed the problem of R&D needs by considering demand from the S&T sectors, and used this data to compare sugarcane electricity to other fossil-based or renewable electricity options. The highest scores go to hydroelectric and solar PV, while the sugarcane bagasse is associated with very low scores due to the reliance on agricultural sectors rather than other parts of the economy.

Summary

Certain aspects of this indicator are well-tracked, particularly when considering the economic analysis of plant or bioenergy supply chain performance, and the cost of CO_2 abatement. These studies are highly impacted by regional or local conditions, and studies that are available do not use identical methodologies and may include different aspects of the supply chain in their analysis. Thus it is difficult to compare the financial sustainability of these systems, or the cost of CO_2 mitigation. In order to be more useful, these studies might apply standardized system boundaries, which would allow comparison across different jurisdictions and biomass supply chains.

There is less literature available on research expenditures, and the literature that is available does not interrogate the question of how much funding is actually being devoted to specific research areas. Individual country government reports are more likely to provide relevant information but it can be difficult to put this information into context. As a measure of sustainability for bioenergy supply chains, investment in R&D needs to be (a) placed in context, so that it is possible to compare investments with other companies/regions/nations; (b) tracked over time, so that it is possible to see changes in the level of investment; and (c) related to outcomes, so that the benefits of R&D can be translated into the impacts it might have on the sector.

SDG 10 - REDUCED INEQUALITIES

Indicator overview

One of the primary impacts of bioenergy development would seem to be the ability to support local economic development (Obidzinski et al. 2012, Burli et al. 2016). Tracking this can be very difficult, however. This measure falls best within SDG 10, and can be approximated using the recommended indicator of *redistributive impact of fiscal policy* (10.4.2) (UN Statistics Division 2022).

Key studies

It is well understood that bio-based innovation creates risk for some along the value chain, particularly those without the funds to take part in the projects or without the capacity to be able to engage in the emerging bioenergy system (Mac Clay, Sellare 2022). Studies have attempted to understand what the local benefits might be of different bioenergy supply chains. In the USA, Saul et al. (2018) examined the use of logging residues and small-diameter trees in local, regional, and international development pathways (Saul et al. 2018). It was pointed out that the numbers of jobs created varied dramatically as the host community changed, due to the geographic distribution of resources and connectivity to markets. When examining a local development strategy, for example, the number of jobs created ranged between 261 and 322 depending on host community; similarly, if a regional strategy was undertaken, the number of jobs ranged between 1,743 and 4,094, while for the international strategy, the number of jobs ranged between 333 and 466 (Saul et al. 2018). These findings highlight the challenges of scale; more benefit may accrue at larger scales, but that benefit may not be linked back to the local community.

Scholars have pointed out the importance of linking the supply chain for bioenergy to other forest or agricultural products. For instance, a study in Norway considered five cases for localized development of bioenergy, and pointed out that in every case the biomass utilized was simply part of a larger forest products supply chain (Forbord et al. 2012). This study highlights the importance of local commitment to building out local bioenergy systems, as well as the need for financial support to establish these networks. Another study – in Oregon, USA – builds on the importance of developing bioenergy within the larger biomass supply network, and highlights the need to understand local needs, in this case the very local demand for heat (Crandall et al. 2017). By focusing on the potential for biomass to meet localized needs, a different strategy emerges than one that is driven by economic returns or by national-level priorities.

Some projects do not necessarily deliver local socioeconomic benefits. In Yucatan, Mexico, 70 semi-structured interviews were conducted across 13 communities, 8 of which were located near jatropha plantations, and 5 of which acted as control sites (Banerjee et al. 2017). The plantations were initially established to meet three policy goals, including diversification of the country's domestic energy production and lowering of energy-related GHG emissions, increasing local employment, and stimulating rural economic development. These policies were introduced in a top-down fashion and did not take into account important information, such as local ecological conditions, which ultimately led to low productivity and the closure of the plantations. Similarly, a study in Latvia found that incentivizing the production of bioenergy feedstocks led to both positive and negative impacts, with the negative impacts associated with environmental and cultural services outweighing the benefits of GHG emission reduction (Melece et al. 2016).

At the present time, a number of projects in Canada have seen Indigenous communities take ownership over their energy supply by employing bioenergy options, including examples in Fort McPherson, Northwest Territories (Buss et al. 2022) and Cold Lake First Nations in Alberta (Mansuy et al. 2020). However, recent work identifies lack of capacity in Indigenous communities across Canada as a major barrier in the face of utilizing bioenergy options, despite access to feedstocks and a pressing local need for cleaner energy (Menghwani et al. 2023).

De Souza et al. (2022) examined this issue by using the GINI index, a measure of national income inequality which can be used to assess inequality among wages from different electricity generation options. They used this approach to compare sugarcane electricity to a range of other fossil-based and renewable electricity options. The results from this analysis were potentially skewed by the relatively low range of wage values in certain sectors, which meant that the scores for all energy types considered ranged between 0.3 and 0.4. This finding highlights the challenge of measuring local benefits.

Summary

This indicator is not well tracked. It is clear that the success of individual projects usually has to do with understanding local conditions and working with local populations. There seem to be a few key factors to consider: (a) the presence or absence of resources within the community to support entry into the bioenergy supply chain; (b) the ability to link bioenergy feedstock development to other sectors (forestry or agriculture); and (c) a strong understanding of local conditions to help determine chances of success.

KEY TAKEAWAYS

As pointed out by some authors, economic impacts can be highly uneven when examined across the bioenergy supply chain, and may deliver more benefits to the larger economy than to the local project (Singh et al. 2021). The present study has considered fourteen indicators that can provide insight into the economic impacts of bioenergy supply chains.

Six indicators are well addressed. (1-3) Economic productivity, per capita income, and numbers of jobs are three indicators associated with decent work and economic growth. These indicators are fairly well tracked, although it was noted that most of the data describing economic productivity was at the regional or national level; similarly, while information is available on potential jobs and income, very little data is available that describes gendered roles within these indicator groups. This is a gap that needs to be addressed and should be more consistently incorporated into study. (4-5) The financial viability of bioenergy plants and bioenergy supply chains, as well as the cost of CO_2 abatement, are relatively well covered within the literature. The primary challenge is understanding system boundaries employed within these studies, which are highly contextualized by local conditions. (6) The role of bioenergy in addressing gender equality is well tracked with respect fuelwood use and the shift to cleaner and less labour-intensive biofuel options.

Seven indicators are poorly assessed in the literature. (1) Trends in work hours are not well described, as a means of determining if people are working different numbers of hours or if bioenergy development is offering additional opportunity. (2-4) Three indicators associated with access to bioenergy are not well tracked, in terms of who is using it, what it costs, or how volatile this pricing is. The issue of who uses bioenergy was also identified as a major gap in social indicators. The review has made it clear that the economic benefits of bioenergy are largely related to its comparison to a reference system; high-cost energy can be more easily offset by bioenergy options. Little to no data is available on who can access these systems (at a local level), or on the volatility of pricing for bioenergy that is likely to be experienced as biomass growth varies over years. (5) The funding for research and development associated with bioenergy chains is also not well tracked, or explored in the literature; the ability of R&D to support new bioenergy development is not made clear. (6) The ability of local populations to be able to access, hold, or own land is also not well addressed, and no data was available that provided gender-based roles in land tenure. (7) The link between education and bioenergy system sustainability is also not well explored, and studies that have considered educational issues provide contradictory results. (8) Finally, there is also relatively little data describing the ability of bioenergy systems to reduce inequality by fostering local economic development.

Moving forward, key priorities should be to (a) develop methodologies to better track ‘retail’ costs of bioenergy, in order to understand the ability of local populations to utilize these energy sources; (b) develop better methods to evaluate the impact of bioenergy supply chains on local economies as well as regional and national-level outputs; and (c) to determine the best ways to evaluate the potential impacts of bioenergy development on land tenure.

Section 3 - Environmental Measures

A summary of environmental measures can be seen in Table 3. The SDGs related to each proposed indicator are identified. In Column A, an Asterix (*) indicates that attendees at the 17 September 2024 workshop suggested that this indicator was of particular importance (note: no indicators are flagged because the workshop did not include environmental measures of sustainability). In Column B, the SDGs are categorized by the clusters identified by Blair et al. (2021), with high (H), moderate (M), and low (L) correlation to bioenergy supply chain sustainability.

Table 3 - Measures of environmental sustainability in bioenergy systems

A	B	SDG	Indicator	Selected literature
	H	7 AFFORDABLE AND CLEAN ENERGY	(1) Total net energy efficiency; (2) Net energy balance, trends in fossil fuel use	Cherubin et al. 2021; de Souza et al. 2023; de Souza et al. 2022; GBEP 2011; Machado et al. 2021; Manara, Zabaniotou 2014; Martinez-Hernandez et al. 2024; Parish et al. 2018; Song et al. 2015a; Song et al. 2015b
	H	13 CLIMATE ACTION	Net carbon emissions, avoided carbon missions, relative changes in GHG emissions, non GHG emissions	Burli et al. 2016 ; Cherubin et al. 2021; Degani et al. 2022; de Souza et al. 2023; de Souza et al. 2022; Fan et al. 2007; GBEP 2011; Iacovidou et al. 2017; McBride et al. 2011; Parish et al. 2018; Parish et al. 2023; Repo et al. 2011; Song et al. 2015a; Song et al. 2015b; van Dam et al. 2009; Wang et al. 2018; Xing et al. 2020; Zabaniotou 2018
	L	14 LIFE BELOW WATER	Optimal application of fertilizers, runoff, water quality	Burli et al. 2016; Cherubin et al. 2021; de Souza et al. 2022; Degani et al. 2022; GBEP 2011; Obidzinski et al. 2012; Parish et al. 2018; Parish et al. 2023; Xing et al. 2020
	H	15 LIFE ON LAND	Trends in local biodiversity index; protected areas; soil quality	Burli et al. 2016; Cherubin et al. 2021; de Souza et al. 2022; GBEP 2011; Obidzinski et al. 2012; Parish et al. 2023; van Dam et al. 2009

SDG 7 - CLEAN AND AFFORDABLE ENERGY

Indicator overview

An important environmental measure associated with bioenergy system development is the proportion of bioenergy that can be introduced into the overall energy mix, which in turn can contribute to reductions in fossil fuel use, improved energy security, and a more positive energy balance for individual nations (GBEP 2011, Cherubin et al. 2021). These measures are part of SDG 7 and can be approximated through the recommended indicator of *renewable energy share in the total final energy consumption* (7.2.1) (UN Statistics Division 2022).

Key studies

A large number of studies have provided measures of the potential contribution that bioenergy systems could provide to the overall energy balance of a country. A study in Brazil examining the integration of bioenergy crop production and livestock management, finding that expansion of a bioenergy/livestock integrated system could utilize 16 million ha and product 89 billion litres of ethanol per year, mitigating up to 250 million tonnes CO_2e and generating $15 billion in profit (de Souza et al. 2023). A comprehensive study examined the potential impacts of bioeconomy development by modeling growth to 2030 using sugarcane, soy, and forest crops in Brazil (Machado et al. 2021). Key takeaways include the need for government support to enable bioeconomy development, and the limits in land use guided by the overarching need to reduce emissions. A wide range of products were considered within this study, including ethylene and propylene, butanol, acrylic acid, polylactic acid, biodiesel, ethanol, and renewable jet fuel as well as bio-based electricity. Scenarios compared 2009 production to a business as usual case as well as two bioeconomy growth scenarios. In both bioeconomy scenarios, energy demand for fossil fuels declines, largely due to the substitution of bioethanol for gasoline. In this study, crude oil demand is reduced by about 27.5 million m^3, and natural gas demand declines by 5 billion m^3. It should be noted that substitution effects (the amount of fossil fuel that is actually substituted by bioenergy options) are not always in a 1:1 ratio, and attention should be paid to this assumption (Cardinal et al. 2024).

Similarly, in Indonesia forest biomass could provide 132 PJ of energy per year (2013), about 50.4% taken from harvest residues and 49.6% from wood processing residues (Simangunsong et al. 2017). In Punjab, India, surplus agricultural residues could be used for energy production. The primary contributor to agricultural residues are cereal crops (75%) and cotton (25%); annual unused crop residues (about 22.3 Mt/year) have a bioenergy potential of 350 PJ/year, or about 1.43% of India's annual primary energy supply (Singh 2015).

Livestock manure used as a feedstock for biogas production could also be useful. Studies have shown that waste associated with cattle and buffalo have the highest potential methane production (0.36 Nm^3/day/head, 0.32 Nm^3/day/head), followed by pigs (0.06 Nm^3/day/head) (Surendra et al. 2014). In a large-scale review of the use of livestock waste (manure) as a feedstock for bioenergy in China, authors suggested that in 2017, 51.12 Mt of waste could be accessible out of a theoretical total of 200 Mt, which could be converted into about 16.92 B m^3 of biogas (Xing et al. 2020). Similar studies in Europe suggested 120 Mt of waste available, which could be converted into biogas in the range of 5.4-39.7 billion m^3 depending on the conversion efficiency; benefits can be achieved using small (3-30 m^3) biogas facilities (Capaccioli et al. 2016).

Some studies provide more localized data. The use of *Pongomia pinnata*, a tree growth in southeast Asia, as a feedstock for biofuel and bioproduct development, has recently been explored (Degani et al. 2022). The ability of these trees to support nitrogen fixation in soils and their ability to support phytoremediation are documented, as well as their ability to grow on marginal lands or used in intercropping systems. The seeds produced by these trees have an oil content of between 15-45%, and the biomass waste generated by oil recovery can be used to support biogas production; for every MJ of biodiesel equivalent produced, 3.46 MJ of biogas can potentially be recovered from these feedstocks.

Energy balance is also a way to assess the sustainability of a system. For example, de Souza et al. (2022) considered fossil energy use within sugarcane-based bioelectricity generation to that of other renewable and fossil-based options. Hydro presents the best of all energy systems considered, while coal is the worst. Sugarcane-based electricity performs very well, because it uses very little fossil energy. Similarly, a study examining switchgrass production suggested a net decrease in fossil fuel production relative to the status quo (e.g. corn agriculture), but did not suggest that this would increase energy security, as corn can also be used as a feedstock for biofuel production (Parish et al. 2016).

Summary

This indicator is well documented, with a number of studies available to provide high-level assessments of the potential contributions of bioenergy. Important components of these investigations are (a) spatial and temporal scope, as there is no standardized approach; (b) clear communication of assumptions with regards to biomass recovery and conversion efficiency; and (c) a clear communication of system boundaries, as these studies are generally restricted to bioenergy sector assessment. As in other measures discussed elsewhere, these studies rarely consider economy-wide impacts, and it is often difficult to gauge the potential impacts of the bioenergy sector on overall energy use. The substitution effect – the amount of bioenergy that actually is substituted for fossil fuels – is also important to take into account.

SDG 13 - CLIMATE ACTION

Indicator overview

One of the most important measures of overall bioenergy system sustainability are the emissions related to bioenergy production and use (van Dam et al. 2009, GBEP 2011, Burli et al. 2016). It is worth noting that many authors suggest tracking these emissions in different ways, including direct vs. indirect emissions, carbon emissions vs. non-GHG emissions, etc. It is also important to note that relative emission reductions is considered to be an important measure. All of these measures can be found within SDG 13, and can be approximated by tracking the recommended indicator of *total greenhouse gas emissions per year* (13.2.2) (UN Statistics Division 2022).

Key studies

There are many studies that have considered GHG emissions associated with bioenergy systems. An investigation of global potential and use of biomass energy showed that using biofuels could reduce CO_2 emissions between 50-70% compared to using fossil fuels (gasoline and diesel) (Demirbas et al. 2009).

Most studies are regional or national in scope. For instance, in the USA, it may be possible to increase carbon in forest ecosystems and traditional timber products by an average of 40 million t CO_2e/year if forest residues are used for energy production (Daigneault et al. 2012). A study in Brazil examining the integration of bioenergy crop production and livestock management suggested that the production of 89 billion litres of ethanol per year could mitigate up to 250 million tonnes CO_2e annually (de Souza et al. 2023). In British Columbia, Canada, researchers found that using harvest residues and wood processing residues in one timber supply area could support a combination of cogeneration, heat, and electricity plants, as well as a pyrolysis plant and a large pellet facility. Operating these facilities could reduce overall GHG emissions by between 2.67 Mt CO_2e/year and 6.84 Mt CO_2e/year (Cambero, Sowlati 2016). The total amount of biomass used, however, is not clear. When considered as part of national or regional energy use, bioenergy substitution has been shown to have multiple benefits in other industries, such as cement production (Ayer, Dias 2018).

Sometimes carbon benefits are calculated on a very localized basis; for example, in the study considering *Pongomia pinnata* for biodiesel and biogas production, it was suggested that individual trees would sequester 767 kg of C over 25 years (Degani et al. 2022). In a study examining the use of winery waste for biorefining, it was found that 2.83 t/ha of waste (pomace) could be generated, leading to reductions in CO_2 emissions by 368 kg/t pomace used, providing a net benefit of about 355 kg CO_2/t pomace once emissions associated with energy used in the process were included (Zabaniotou et al. 2018). The use of biochar as a soil amendment could increase avoided emissions by 2-5 fold compared to using biochar to offset fossil energy (Gaunt, Lehmann 2008).

China has been particularly well documented in the literature. In China, the capture of livestock waste could create 16.92 B m^3 of biogas, equivalent to about 330-360 PJ of energy per year using a lower heating value of 21 MJ/m^3; it should be noted that this translates to about 331 m^3/tonne of manure, which is a very high figure compared to other published data. The use of these fuels could result in an emissions reduction of approximately 27 Mt of CO_2e per year (Xing et al. 2020). Another study in Jilin Province, China, examining the use of 47.1 Mt of straw biomass for energy production (Wang et al. 2018). This work suggests that a combination of direct combustion, briquette fuels, and cellulosic ethanol could be generated resulting in a reduction in overall GHG emissions by 700 Mt of CO_2e. Studies in China suggest that bioelectricity and biofuel use could lead to a 31% reduction in cumulative greenhouse gas emissions over the study period (Song et al. 2015a, Song et al. 2015b). Assessments suggest that using industrial wastes, livestock and human waste, crop residues, and food processing wastes, and municipal wastes in China could displace 0.4 billion tones per year of coal and 3.75 million tonnes per year of oil, which overall would reduce carbon emissions by 1.07 billion tonnes per year (Fan et al. 2007).

Other studies have focused on relative greenhouse gas emission reductions. For example, GHG reductions for biodiesel production from soybeans compared to a diesel reference system were estimated to be between 16% and 93% over a 20-year period; for switchgrass production, GHG reductions range from 88% to 117% over the same period (van Dam et al. 2009).

Work has been done at the household level to understand bioenergy use and greenhouse gas emissions, primarily in relation to improved cookstove use. Kenya is ahead of Rwanda in adopting more efficient stoves; 42% of Kenyan households have improved stoves but Rwanda and other nations fall behind. Adopting improved cooking stoves was shown to have a dramatic improvement over conventional, three-stone stoves; depending on the model, , reduce emissions by between 0.13-0.55 t CO_2e/year, and finally reduce deforestation by up to 0.03 ha/year (Uwizeyimana et al. 2024). In other African countries, improved cookstoves provided similar greenhouse gas emissions reductions in each country examined, ranging from 2.74 t CO_2e/household/year (Senegal, Guinea-Bissau) to 2.93 t CO_2e/household/year (The Gambia) (Mazorra et al. 2020). Similarly, in a review of the use of biogas plants in Bangladesh, it was estimated that the use of a household gasifier is estimated to prevent the release of 2.5 t of CO_2 per year compared to burning biomass (Rahman et al. 2019). Introducing biogas in China reduced total CO_2e emissions at the household level by between 11% and 37% (Gosens et al. 2013).

Another way to consider GHG emissions is through the concept of carbon debt, although this measure is not widely used. A study in Canada compared the GHG benefits associated with salvaged timber and forest harvest residues for heat and power, finding that carbon debt associated with salvaged trees could take up to 100 years to be paid out before carbon benefits begin to accrue, while harvest residues have a much faster payback, particularly if those residues are currently being burned at the roadside (Mansuy et al. 2018). The importance of understanding the baseline reference system is underscored in this article, which considered both heat and power outputs as well as coal, oil, and natural gas as fossil fuel systems. When substituted for heat, payback times for carbon debt ranged from 5-15 years for harvest residues when using coal as a reference system, from 8-12 years compared to oil, and from 25-65 year compared to natural gas. Payback periods for salvaged trees ranged from 25-90 years compared to coal, from 41-100 years compared to oil, and were greater than 100 years compared to natural gas. Similarly, when substituted in electricity generation, payback times for harvest residues ranged between 10-32 years for coal, from 21-68 years for oil, and extended beyond 100 years for natural gas, while payback times for salvage timber ranged from 55-100+ years for coal, from 96-100+ years for oil, and in excess of 100 years for natural gas. Note that in all cases, harvest residues diverted from roadside burning begin to offer GHG emission reduction benefits in year 1.

Finally, de Souza et al. (2022) used global warming potential (a measure of GHG emissions) to compare sugarcane electricity to fossil-based and renewable electricity generation alternatives. Oil based electricity has the worst aggregated result, while wind has the best, followed closely by sugarcane electricity.

Summary

This indicator is well documented in the literature. Most studies investigating impacts of bioenergy systems make an attempt to understand greenhouse gas emissions, either as an absolute measure or relative emission levels compared to a reference system. There is little commonality in terms of how these emissions are represented – they may be related to amounts of biomass used, amount of energy generated, etc. To increase the utility of these measures, it would be helpful to provide guidance in terms of functional units.

SDG 14 – LIFE BELOW WATER

Indicator overview

The impact of bioenergy systems on water systems is considered to be an important measure of overall sustainability, particularly as measured by eutrophication of marine systems (Burli et al. 2016, de Souza et al. 2022). This is captured within SDG 14 and can be approximated using the recommended indicator of *index of coastal eutrophication* (14.1.1) (UN Statistics Division 2022).

Key studies

A few existing studies have considered marine eutrophication, which is primarily associated with the runoff of chemicals and fertilizers form fields into rivers and ultimately into marine systems. De Souza et al. (2022) assessed marine eutrophication, along with marine ecotoxicity and aquatic acidification, to compare sugarcane electricity systems with other electricity generation options, including fossil-based and renewable systems. The aggregate results indicate that hydro performs the best, and coal performs the worst, while sugarcane electricity performs in the top half of the range. When looking at the use of agricultural residues and dedicated bioenergy crop (giant reed, *Arundo donax*), one study saw impacts to both water reservoirs and to GHG emissions (Anejionu et al. 2020). A variety of scenarios were considered, including ones in which water was recycled for reed production, and one in which food and fuel production was optimized. In most scenarios, water reservoirs were seen to decline, although habitat quality and connectivity rose. There were negative impacts on eutrophication associated with these systems.

It may be possible to improve water conditions by using bioenergy systems which in turn take up excess nutrients from the landscape. Xing et al. (2020) report substantive reductions in photochemical oxidation, eutrophication, and acidification impacts that would affect aquatic and terrestrial ecosystems by capturing livestock waste for biogas production. These types of benefits, already mentioned with reference to a previous indicator, should be tracked.

Summary

This indicator is moderately well measured in the literature, although it can be difficult to connect bioenergy production itself to the levels of eutrophication which are observed. As with many indicators, eutrophication is closely related to farming practices and thus part of a complex system of which bioenergy is simply one component. In general, systems which see increased use of fertilizers and herbicides are likely to see increased eutrophication, but some bioenergy systems can be designed to utilize excess nutrients and thus reduce water impacts.

SDG 15 - LIFE ON LAND

Indicator overview

The development of bioenergy systems will have impacts on the landbase, as biomass flows are redirected towards energy uses or as area is set aside for biomass production. Measures that can help describe these impacts include trends in local biodiversity and evaluations of soil quality (Burli et al. 2016, Cherubin et al. 2021). These measures are captured within SDG 15, and can be approximated through two of the indicators suggested by the UN, including the *integration of biodiversity into national accounting and reporting systems* (15.9.1), the *proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type* (15.1.2), and the *proportion of land that is degraded over total land area* (15.3.1) (UN Statistics Division 2022).

Key studies

Bioenergy systems could lead to substantial changes to the use of land. A study examining switchgrass cultivation in Iowa, USA, explored land use scenarios to deliver increased cellulosic biomass to a biorefinery (Parish et al. 2023). This study suggested that an optimum scenario would involve replacing 10% of the landscape, representing least-productive rows of corn, with switchgrass, while increasing corn stover recovery and in some cases increasing the amount of land planted with grasses under the Conservation Reserve Program. A variety of environmental indicators were reviewed. Findings indicated benefits in terms of biodiversity, soil quality, soil carbon, water and wind erosion control, water quality, increased feedstock for both food and fuel, better use or residues, and decreased fertilizer use. However, the study also found that methane emissions could rise compared to the status quo.

Land-use change is a critical issue related to bioproducts development. A study considered the implications of sugarcane development for bioenergy production in Brazil, and applies lessons learned to putative development of sugarcane plantations in the Caribbean and sub-Saharan African countries (Cherubin et al. 2021). This project highlighted the challenges in biomass crop expansion, as substituting sugarcane for native forest or pastureland leads to short-term decreases in soil carbon and overall soil health, while cropland conversion can lead to increased carbon sequestration and improved soil health. This paper focuses on best management techniques to maintain soil health and carbon while optimizing crop residue recovery.

The impact of bioenergy supply chain development was measured by de Souza et al. (2022) through land use change and ecosystem impacts; the data compiled was used to draw comparisons between sugarcane electricity systems and both fossil-based and renewable electricity generation options. In terms of land use change and ecosystem impacts, oil has the worst aggregate result, and wind has the best result, followed by solar PV and then sugarcane bagasse electricity. Parish et al. (2016) also considered environmental indicators related to switchgrass production in Tennessee, USA (Parish et al. 2016), including soil quality, and found that improvements were seen in the majority of these systems when comparing switchgrass production to tilled corn production.

The assessment of environmental benefits carried out by van Dam et al. (2009) also identified some interesting trends, finding that the best bioenergy systems were established on abandoned cropland, where annual soil loss ranges from only 0-2 t/ha/year. Lower scores tended to be on degraded grasslands due to the added impact of bringing these fields into agricultural service. Soil carbon stocks are also expected to increase on these types of lands, for switchgrass, between 0.2 and 1.2 t /ha/year, and for soybean production, a range between -1.2-0 t C /ha/year (van Dam et al. 2009). There is potential to improve soil conditions with judicious bioenergy system deployment.

Summary

This indicator is fairly well documented. Bioenergy systems can have negative impacts on the landbase but can also be designed to help rebuild soil carbon. Soil degradation is most widely measured within this space; there is less data about protected area use, and very little data on biodiversity. Overall, the bioenergy systems which have the most benefit are those that can provide positive soil performance, allowing carbon to return to the landscape and requiring little in terms of soil amendments or fertilizer inputs.

KEY TAKEAWAYS

This review considered five indicators to measure the environmental impact of bioenergy supply chains. Of these measures, three were well documented in the literature. (1-2) Total energy balance, trends in fossil fuel use, and energy efficiency are widely reported in the literature for different bioenergy systems, providing helpful guidance on the potential substitution of bioenergy options for fossil fuels within national or international energy systems. (3) Carbon emissions are well documented, although the functional unit used varies and comparing data between different studies can be challenging.

Two other indicator groups are moderately well documented. (1) With respect to the impact of bioenergy systems on life on land, soil quality is well explored, and the relation between bioenergy systems and soil carbon or soil degradation is widely documented. The impacts of bioenergy systems on biodiversity is less well documented and presents a more substantial challenge in data collection. Little work has been done to document the impact of bioenergy systems on protected areas. (2) There is some work connecting bioenergy systems to eutrophication in marine waters, primarily due to the presence of nutrients and fertilizers in runoff.

Moving forward, priorities are likely to (a) improve methodological approaches, particularly related to system boundaries, to better situate bioenergy production systems within our understanding of forest and agricultural land use, which will help to better elucidate impacts on soils, biodiversity, protected areas, and water systems; and (b) to improve reporting on greenhouse gas emissions by introducing guidance on functional units, which will allow studies in this area to be more easily compared.

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