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Contribution of Biomass Supply Chains for Bioenergy to Sustainable Development Goals

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Abstract: This work evaluates the relationships between bioenergy and related biomass supply chains and the United Nations Sustainable Development Goals (SDGs). Using Nilsson et al. (2016) seven-point scoring framework, the relationships between biomass supply for bioenergy and the SDGs were evaluated based on existing synthesis papers, modeling studies and empirical analyses, and expert knowledge. To complement this, contributions to SDG targets of 37 best practice case studies from around the world were documented. In reviewing these case studies, it was found that when supply chains are implemented appropriately and integrated with existing systems, they can have overwhelmingly positive contributions. Beyond directly contributing to SDG 7 (Affordable and Clean Energy), at least half of all case studies supported progress toward SDGs 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), and 12 (Responsible Production and Consumption); however, the ways in which supply chains contributed often differed. Agricultural biomass supply chains (energy crops and residues) were most likely to contribute to SDGs 2 (Zero Hunger) and 6 (Clean Water and Sanitation), while waste and forest supply chains were most likely to contribute to SDG 15 (Life on Land). The development of bioenergy systems in rural and indigenous communities also indirectly supports societal SDGs such as SDGs 1 (No Poverty), 4 (Quality Education), 5 (Gender Inequality), and 10 (Reduced Inequalities). This work informs how SDGs can be used as a normative framework to guide the implementation of sustainable biomass supply chains, whether it is used for bioenergy or the broader bioeconomy. Recommendations for key stakeholders and topics for future work are also proposed.

Keywords: biomass; bioenergy; supply chains; sustainable development goals

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1. Introduction

The United Nations (UN) Sustainable Development Goals (SDGs) were adopted by all UN Member States in 2015. The 17 SDGs (Appendix A Table A1) are part of a 15-year plan to achieve the UN's 2030 Agenda for Sustainable Development. The SDGs serve as a comprehensive framework to guide actions in all sectors of human activity [1], embodying a message conveyed more than 30 years ago in *Our Common Future* [2] that policies, including climate and energy policies, should not be developed in sectoral silos but rather seek synergies with other societal goals.

The SDGs apply to all countries regardless of economic status and serve as the cornerstone for national sustainable development strategies. Annual progress towards achieving these goals is reported on also by the UN [3]. In addition, given their comprehensiveness and global scope, the SDGs are increasingly being adopted by the private sector to develop corporate social responsibility (CSR) frameworks and practices, and improve the development of international standards [4,5].

As the SDGs are increasingly being used to frame government and corporate strategies, the increasing adoption of renewable and sustainable energy systems as part of local, national, and international climate change plans will require a holistic approach that recognizes a multitude of objectives, as outlined in the SDG framework. Such an approach is particularly important for the sustainable production of bioenergy, as it relies on biomass—any organic matter available on a renewable basis—for which growth, harvest, collection, storage, transport, or processing can have significant environmental, socio-economic, and health impacts for people and their communities [6]. Impacts can be overwhelmingly positive for a given region but concerns exist regarding the potential negative impacts, particularly if biomass supply for bioenergy is significantly increased over the coming years and decades [7].

Bioenergy is the largest source of renewable energy, making up 9.6% of the world's total energy supply (55.6 EJ in 2018) [8]. Roughly half of this bioenergy supply comes from *traditional* applications such as wood-burning fires and cookstoves [8]. However, traditional bioenergy is expected to decline as *modern* equipment and systems, designed to increase energy efficiency and reduce air pollution, are deployed in developing countries and emerging economies [9,10]. A significant increase in sustainably procured biomass is expected with the predicted growth in bioenergy generation as countries increasingly adopt climate change and bioeconomy policies [8,10,11]. Much of the additional biomass will likely be sourced from waste and residue streams, but purpose-grown crops are expected to play an increased role [7,12].

A number of studies have assessed various aspects of the sustainability of bioenergy systems and biomass supply chains at the field, regional and national level, with an increasing focus on social and economic sustainability in addition to environmental sustainability [13,14]. However, 'sustainability' has been interpreted differently across a number of these studies using various methodological frameworks to assess a variety of biomass supply chains and bioenergy systems making comparative evaluations difficult [13]. Given this, two internationally recognized frameworks have been developed to assess the sustainability of bioenergy systems (the Global Bioenergy Partnership (GBEP) sustainability indicators [15] and the International Organization for Standards (ISO) 13065 Standard on Sustainability Criteria for Bioenergy [16]) but are not yet widely applied and their implementation is not explicitly tied to the SDGs.

A handful of recently published studies and reports explicitly draw connections between bioenergy and/or biomass supply and SDGs generally, without differentiating between biomass supply chains [7,17–22]. Some studies examine the links between the bioeconomy and the SDGs broadly [19,21], while others examine more closely the relationship between biomass for food and feed and bioenergy [7,18]. There is, however, general agreement that bioenergy is most likely to be linked, either positively or negatively, to SDGs related to food security and sustainable agriculture (SDG 2), decent work and economic growth (SDG 8), resilient infrastructure, and sustainable industry (SDG 9), responsible consumption and production (SDG 12), climate action (SDG 13) and terrestrial ecosystems (SDG 15), in addition to SDG 7 (affordable and clean energy) [7,17–22]. Some authors have also suggested that bioenergy systems are moderately linked to 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) [7,17,19,21,23]. The remaining SDGs are less likely to be related to bioenergy systems but may be indirectly linked, or linked to certain supply chains in certain regions, and 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).

Building on existing research and frameworks, this work aims to outline the role that biomass supply chains developed for bioenergy production can play in achieving the SDGs while highlighting precautions to avoid adverse effects. The SDGs will be used as a normative framework to characterize possible interactions with other SDGs when biomass is deployed as a renewable energy source to contribute to SDG 7, target 7.2 (increase substantially the share of renewable energy in the global energy mix). This characterization is done based on published literature, at the target level, distinguishing biomass by type, and by end-use versus biomass supply. Following this, a set of bioenergy case studies are analyzed to examine whether the relationships identified hold true in real life. These case studies are used to help identify synergies between SDG 7 and the other SDGs when biomass supply is used for bioenergy production in pursuit of achieving target 7.2. A discussion on how the analysis could be applied for different stakeholders, and possible future work, is provided.

2. Methods

The systematic assessment of biomass supply for bioenergy production and its contribution to the SDGs was carried out in two steps. First, an existing scoring framework was used and expanded upon to examine the relationships documented in the current literature between biomass supply chains and SDGs at the target level, and the nature of these relationships where they do exist. To complement those results, 37 case studies were also reviewed to identify and compare the prevalence and nature of these relationships between biomass supply chains and SDGs in practice.

2.1. Scoring Framework for Links between Bioenergy Supply Chains for Bioenergy Production and SDGs

This study applied the seven-point scoring framework proposed by Nilsson et al. (2016) [24] to examine relationships, both positive and negative, between biomass supply chains and the SDGs reported in the current literature (Table 1). This framework has since been applied to assess the relationships between SDG 7 (affordable and clean energy) and other SDGs based on a systematic review of the literature [23]. The assessment for the current study builds on this application of the Nilsson et al. (2016) framework but specifically examines how biomass used for bioenergy in pursuit of target 7.2 interacts with other SDG targets. Positively scored interactions represent an opportunity for synergies, acting as a lever for cross-sectoral strategies, while negatively scored interactions highlight areas where decisions must be made on potential trade-offs.

Table 1. Scoring framework developed by Nilsson et al. (2016) [25].

Interaction	Score	Explanation
Indivisible	+3	Inextricably linked to the achievement of another goal
Reinforcing	+2	Aids the achievement of another goal
Enabling	+1	Creates conditions that further another goal
Consistent	0	No significant positive or negative interaction
Constraining	−1	Limits options on another goal
Counteracting	−2	Clashes with another goal
Canceling	−3	Makes it impossible to reach another goal

As part of the analysis, it was indicated whether the interactions identified were related to the generation of energy itself (bioenergy end use), or to the supply of biomass for bioenergy (biomass supply). Interactions specific to certain types of biomass supply chains were also indicated. The four supply chains types considered in the analysis are those that are most likely to be used for modern bioenergy generation globally [9,12]:

- **Forest** biomass includes harvest residues such as treetops, branches, and unmerchantable stems, as well as wood processing residues such as wood chips, sawdust, and shavings.
- **Agriculture residues** consist primarily of the biomass remaining after crops are harvested (e.g., wheat straw, corn stover) but also include food or feed processing residues such as corn cobs, olive pits, or grape marc.

- **Energy crops** are purpose-grown for bioenergy production, which can also include food crops (e.g., sugar cane, oil palm, corn) redirected to bioenergy production. Energy crops are most often perennial and can be woody (e.g., poplar or willow) or herbaceous (e.g., switchgrass). Annual cover crops can also be used for bioenergy.
- **Waste** of biological origin includes primarily animal (manure) and household, commercial or municipal organic waste.

Each of the authors independently scored the relationships with SDG targets using the seven-point scale in Table 1. To inform the assessment, the authors relied on a broad range of synthesis papers, modeling studies, and empirical analyses of bioenergy and biomass supply chains. Supply chains could be scored both positively and negatively for the same SDG, or even the same target, as either may be possible depending on how they are designed and implemented. To help in the interpretation of the current literature, the diverse expert knowledge of the authors was complemented by input from members of several IEA Bioenergy tasks. Diverging views, inevitable given the subjective and complex nature of the evaluation, were resolved and a consensus was reached among the authors on all scores presented in the results.

In addition to scoring, the interactions were categorized by type, expanding on the *driver* and *safeguard* categories proposed in Reference [7]. This adds an additional level of analysis and better describes the nature of the relationship between a supply chain and a SDG target, something not found in the current literature. The categories used are:

- **Driver for bioenergy**: Achieving the target is a driver for the development of bioenergy and biomass supply chains. Bioenergy is implemented to directly contribute to the SDG.
- **Driver for competing use**: Biomass is required for or could be used for, non-energy purposes (e.g., food, feed, biomaterials) to achieve the target.
- **Safeguard**: Negative impacts to avoid; a commitment to achieve the target prevents (or "safeguards against") potential negative consequences and helps to ensure best practice in the production and mobilization of biomass for bioenergy.
- **Co-benefit**: Bioenergy development has positive repercussions on achieving the SDG or becomes more attractive because of synergies with the SDG.
- **Enabler**: Progress toward this SDG may facilitate or accelerate the development of sustainable bioenergy and related biomass supply chains.

2.2. Analysis of Case Studies

The case studies used to compare and evaluate the results from the supply chain scoring exercise with real-life supply chains were chosen primarily from the existing literature, specifically three recent IEA Bioenergy/GBEP reports, that exemplified best practices related to biomass supply for bioenergy [25–27]. These cases were selected to examine the role that bioenergy can play in achieving the SDGs now and in the future when the appropriate safeguards are in place. Additional cases were selected from the current literature, or from the authors' first-hand knowledge, to ensure a variety of supply chains and end uses throughout the world were represented.

Data on each case study's location, ownership, logistics and operations, and bioenergy conversion and end-use were compiled from the identified reports and literature. Incomplete data were supplemented, where possible, with other sources, including publications, academic presentations, or author's knowledge of a case study. A database was created to collect this information. In addition to contributions of case studies to SDGs, four variables were considered for this analysis: (1) project status (implemented, in the planning stages, or studied); (2) biomass supply chain type (forest biomass, agricultural residue, energy crops, waste); (3) location (continent); and (4) bioenergy end-use. Positive contributions and negative impacts on SDGs were recorded only if there was a documented description (qualitative or qualitative) in the case study. Fields within the database were documented and/or validated by experts with knowledge of the case studies or their context. The relationships between SDGs and biomass supply chain types, location, status, and end-use of the case studies were examined and discussed within the context of the potential relationships identified in the scoring exercise. Other details and further discussion of the case studies, along with complete descriptions of each case, will be available as an IEA Bioenergy report in 2021. The variables selected for analysis were those that the authors felt, based on their own knowledge and the literature review, were most likely to be associated with SDGs.

3. Results

3.1. Scoring

The scoring exercise examined the relationships between biomass supply chains established for bioenergy production in pursuit of SDG 7, target 7.2, and other SDG targets, highlighting possible synergies and tradeoffs. Scoring results for SDGs with a high likelihood of being linked to bioenergy are provided in Tables 2–8. For SDGs with a moderate or low likelihood of being linked to biomass supply, detailed tables are provided as supplementary material (Table S1 and S2). In addition to the scores, the tables provide the nature of the interaction (category) and a brief description and key references. The "linked with" column indicates whether an interaction applies to (1) a specific supply chain; (2) supply chain activities, regardless of type (all-supply); or (3) the generation of bioenergy (all-use). While scores of +/−3 were included in the scoring scale, such relationships between biomass supply for target 7.2 and other SDG targets were not found.

Table 2. Scoring of synergies and trade-offs between biomass deployed in pursuit of target 7.2 and Sustainable Development Goal (SDG) 2.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
2 Zero Hunger	Support Small-Scale Producers (2.3)	Ag. Residue/Energy Crop	+2	Driver/co-benefit	Revenue from crop residues often boosts incomes and increases the productivity of small-scale food producers but there is a trade-off between revenues from residues and cost of soil amendment due to removal.	[27–29]
	Sustainability, Productivity of Food Production (2.4)	Ag. residue	+1	Co-benefit	Crop residues used for energy do not need to be disposed of in other ways (e.g., burnt, landfilled). Existing equipment can be leveraged to process residues in the off-season, or with primary crop. Both factors improve the sustainability and productivity of agriculture practices.	[20,29,30]
			−1	Safeguard	Indiscriminate residue removal may negatively impact soil quality (removal of nutrients and organic matter) and reduce yields or increase the need for fertilizer.	[31,32]
		Waste	+1	Co-benefit	Digestate from anaerobic digestion can be applied to crops as fertilizer, reducing the need for synthetic fertilizer or improving productivity for farmers who could not afford fertilizer.	[33,34]
	Food Security, sustainable agriculture (2.1, 2.4)	Energy crop	+1	Co-benefit	Energy crops can be integrated with food crops to enhance agricultural yields/productivity and promote the mechanization of agricultural practices	[35–37]
			−2	Safeguard	Energy crops may compete with food crops for land and resources, potentially leading to higher food prices and reduced access to food. Enhanced productivity and integrated resource management can allow a variety of crops to be produced on as little land as possible.	[18,23,36]

Table 3. Scoring of synergies and trade-offs between other targets under SDG 7 and target 7.2.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
7 Affordable Clean Energy	Affordable, Efficient Energy (7.1)	All-use	+2	Driver	Bioenergy systems, particularly for heat, have the potential to reduce energy costs relative to existing fossil fuel or electric heating systems.	[28,38–42]
		All-use	−2	Safeguard	Bioenergy could also increase energy costs, particularly for transportation fuels and electricity without cogeneration.	
	Energy Efficiency (7.3)	All-use	+1	Co-benefit	Bioenergy can be integrated with other forms of renewable energy to provide balance and enable expansion of intermittent renewables.	[18,20,28,43–46]
		All-use	−1	Competing use	Bioenergy may compete with other forms of low carbon or renewable energy for market share. Non-renewables should be phased out through an overall increase in renewable energy generation.	

Table 4. Scoring of synergies and trade-offs between target 7.2 and SDG 8.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
8 Decent Work, Economic Growth	Economic Development, Employment (8.1, 8.2, 8.5, 8.6)	All-supply (and use)	+2	Driver/Co-benefit	Increased biomass demand may result in economic growth at the community and regional level, especially in rural areas, due to significant employment opportunities associated with biomass supply. Community-scale bioenergy projects can create local opportunities for apprenticeships and revenues for municipalities.	[18,28,40,47–53]
	Strong Financial Institutions (8.10)	All-use	+1	Enabler	To support bioenergy, strengthened financial institutions (particularly in developing countries) are necessary for providing capital, credit, and insurance to entrepreneurs.	[18,23]
	Sustainable Tourism (8.9)	Forest	+1	Co-benefit	Examples exist of forestry communities that have turned their forest bioenergy system into a tourist attraction. Managed forests are often more accessible for recreation than unmanaged forests.	[47,48]
			−1	Competing use	Forests surrounding rural communities often form the basis of their tourism industry. Concerns sometimes exist about ecosystems being degraded due to increased biomass harvest and negatively impacting tourism.	[52,53]

Table 5. Scoring of synergies and trade-offs between target 7.2 and SDG 9.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
9 Industry, Innovation, Infra-structure	Sustainable Infrastructure and Industrialization (9.1, 9.2, 9.4)	All-use	+2	Co-benefit	Bioenergy displaces fossil fuels for thermal and electrical industrial energy needs, reducing CO_2 intensity of industry and infrastructure. Biomass district heating directly contributes to the goal of developing sustainable, reliable infrastructure.	[4,41,47,54–56]
	Support for Industry and Infrastructure (9,3, 9.5, 9.a, 9.b, 9.c)	All-use	+1	Enabler	Improved access to financial services, increased research and development efforts, industrial efficiency programs, support for sustainable infrastructure, and enhanced access to the internet and information all could support bioenergy.	[23,57,58]
	Emission Reduction (9.4)	Forest/ Ag. Residue	+2	Driver/co-benefit	Significant CO_2 reduction (near term) can be achieved if open-air burning of residues is reduced due to use for bioenergy. A market for forest biomass provides an opportunity for improved management and a long-term increase in carbon storage relative to current practice.	[30–32,55,59–65]
			−2	Safeguard	CO_2 emissions may increase if crop or forest residues are removed at an unsustainable rate, or if forests are harvested solely for bioenergy, or at the expense of long-lived products.	
		Energy crop	+2	Driver/co-benefit	Planting energy crops for bioenergy production could help lower the overall level of CO_2 in the atmosphere by acting as carbon sinks (when planted on degraded land or displaces annual crop) while in turn producing lower carbon fuels.	[36,66,67]
			−1	Safeguard	Energy crops may lead to reduced carbon sinks if natural landscapes (i.e., forest, wetland) displaced.	
		Waste	+2	Driver/co-benefit	GHG emissions are reduced through the displacement of fossil fuels, and by reducing methane emissions from landfills, farms (manure), and other waste facilities	[33,68,69]
			−2	Safeguard	Possibility of biogas leakage from digestors risks emissions increase	[70,71]

Table 6. Scoring of synergies and trade-offs between target 7.2 and SDG 12.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
12 Sustainable Production and Consumption	Political Support (12.1, 12.6. 12.7, 12.c)	All-supply	+2	Enabler	Bioenergy may be supported as part of national sustainable consumption and production plans, or by other policies supporting sustainable business practices or procurement programs.	[72,73]
	Knowledge and Capacity Building (12.8, 12.a)	All	+1	Enabler	Improved education and awareness surrounding sustainable consumption, and improved technological capacity may advance bioenergy, particularly in developing countries.	[18,21,23]
	Sustainable, Efficient Use of Resources (12.2, also 8.4)	Forest/ Ag. residue	+2	Driver/co-benefit	Use of residues for energy results in more efficient use of resources, and lower material footprint than extracting and burning fossil fuel, especially if residue previously unused or burnt.	[18,28,30–32,49,59,61,74,75]
			−2	Safeguard	If removal of residues is too intense, it may reduce soil quality or crop/forest productivity, and inputs of fertilizers and material footprint may increase. Fiber may be diverted from higher priority uses, e.g., food, construction materials.	[34,69]
	Waste generation, treatment (12.4, 12.5)	Waste	+1	Driver/co-benefit	Potentially hazardous waste streams can be diverted/captured to generate energy. Waste to Energy (WTE) may increase the recovery of metals.	[68,69,76]
			−1	Safeguard	Digestate, generated via anaerobic digestion of waste streams can impact the environment if not treated properly. If waste is used for energy, there may be less incentive to improve recycling.	[34,69]

Table 7. Scoring of synergies and trade-offs between target 7.2 and SDG 13.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
13 Climate Action	Climate-Related Policies (13.1, 13.2, 13.a)	All-use or supply	+2	Driver/Enabler	Bioenergy may be supported as part of a national or sub-national risk reduction strategy or climate change mitigation or adaptation plan.	[77]
		All-supply	−2	Competing use	Policies aimed at emission reduction in the energy sector may lead to land-use change or increased emissions in another region/country, or competition for biomass between bioenergy and other bioproducts	[23]
	Knowledge and Capacity (13.3, 13.b)	All-use	+1	Enabler	Bioenergy likely to be supported in countries that have incorporated climate change into curriculums and are strengthening capacity-building efforts.	[23]

Table 8. Scoring of synergies and trade-offs between target 7.2 and SDG 15.

SDG	Target(s)	Linked with	Score	Category	Interactions Identified	References
15 Life on Land	Protected Areas (15.1)	All-supply	−1	Competing use	Biomass supply could be limited by the existence of, or put pressure on, protected areas.	[78,79]
	Policies for Ecosystems (15.8, 15.9, 15.a)	All-supply	+1	Enabler	Bioenergy may be supported by policies and funding to improve biodiversity and health and function of ecosystems (e.g., to restore degraded agriculture land, reduce pollution or develop sustainable management plans).	[80–82]
	Land Degradation and Biodiversity (15.2, 15.3, 15.5)	Ag. Residue	−2	Safeguard	Indiscriminate residue removal may result in reduced soil quality and land degradation, biogeography of the region can impact sensitivity to the negative impacts of removal. Removal may also result in reduced soil biodiversity.	[30–32,83]
		Energy crop	+2	Driver/co-benefit	Energy crops can be planted on marginal or degraded land and have been shown to improve soil quality over time. Deforested land may be re-planted with agroforestry crops. Land degradation neutrality targets can be a driver for energy crops to restore degraded land.	[18,36,66,84,85]
			−2	Safeguard	Planting energy crops could lead to undesirable land-use changes, reduced ecosystem services, or loss of biodiversity if natural landscapes are displaced. Production of energy crops on degraded land is rarely profitable in practice.	
	Healthy, Productive Forests (15.1, 15.2)	Forest	+1	Driver/Co-benefit	A market for biomass provides opportunities for improved forest management and may also mean that more areas remain forested if profitability is improved due to biomass value.	[61,63,75,86]
	Forested Area, Biodiversity (15.1, 15.5)	Forest	−1	Safeguard	Unsustainable forest biomass harvest/removal could lead to deforestation or loss of biodiversity. Conversion from natural forest to plantation in response to increased biomass demand could also lead to biodiversity losses.	[87,88]

3.1.1. SDGs with a High Likelihood of Being Linked to Biomass Supply for Bioenergy

The supply of agricultural biomass (residues, purpose-grown crops or animal waste) is intrinsically linked to SDG 2 as supply chains are typically integrated with food production systems. Careful integration ensures that biomass supply does not negatively impact soil quality, productivity, or compete with food crops for land and that farmers will benefit from crop diversification, improved productivity, or more sustainable land management practices

Biomass supply for bioenergy production is directly linked to target 7.2 but is also connected to the other targets within SDG 7. Integrating bioenergy into energy systems can contribute towards affordable and efficient energy, but needs to be done in a way that complements other renewables.

Collecting, transporting, and processing biomass of any type is labor intensive; therefore, new supply chains create new economic opportunities locally, regionally, and nationally and contributing to SDG 8. The needs of other industries relying on the forest and other natural landscapes must be considered.

Supplying biomass for bioenergy directly supports SDG 9 by contributing to emissions reductions across economic sectors as a source of heat, electricity, or transportation fuel. The collection and use of biomass must consider impacts on biogenic carbon cycles, including land-use change.

Biomass supply for bioenergy can contribute to SDG 12 through improving resource use efficiency, reducing the need for fossil fuel extraction, and enabling more environmentally sound waste management. Again, its production, collection, and processing must be done sustainably to prevent environmental adverse effects or increased need for fertilizers and other inputs.

The supply of biomass for bioenergy, and the use of bioenergy, is highly linked to SDG 13 as it can be included in national and sub-national climate change strategies. Balance needs to be achieved between other options for biomass use or land management that also provide climate benefits.

Biomass supply has clear implications for SDG 15 because it is primarily derived from terrestrial sources across all supply chains. When managed, intercropped, or collected sustainably, biomass production systems can act as a carbon sink and natural filtration system for air, soils, and watersheds. However, if done unsustainably, activities on the land can also negatively impact local and regional ecosystems.

3.1.2. SDGs with a Moderate Likelihood of Being Linked to Biomass Supply for Bioenergy

SDG 1 is primarily a co-benefit as access to modern bioenergy sources can provide jobs and new economic opportunities for people (targets, 1.1, 1.2, 1.4) [23,89,90]. Well-designed bioenergy supply chains and systems can also reduce dependency on imported fuel sources and increase energy resiliency in communities (target 1.5 exposure and vulnerability) [47,91]. SDG 1 may be a safeguard due to the need to ensure bioenergy systems are not monopolized, further increasing poverty (targets 1.1, 1.2, 1.4) [23,89,90].

SDG 3 is often a co-benefit of modern bioenergy development as health risks and mortality related to contamination and air pollution when replacing diesel, fuel oil, kerosene may be reduced when bioenergy is produced using modern, efficient equipment [33,92–94]. Energy crops can also remove pollutants from the air, water, and soil [18,25,95]. SDG 3 is also a safeguard in that it must be ensured that the development of bioenergy facilities does not lead to increased air pollution or release of harmful chemicals (target 3.9) [89,94].

SDG 6 is primarily a safeguard as bioenergy and biomass supply must not negatively impact water quality (target 6.3), water availability (target 6.4), or otherwise degrade waterways (target 6.6) [25,27,29,31]. Removal of residues from crops can increase the susceptibility of soil to wind and water erosion, due to lack of ground cover [29,31]. Energy crops and reforested areas can also be co-benefits, or even drivers, as they can filter pollutants, reduce runoff, or even treat wastewater, particularly if planted on degraded land, or to replace annual agriculture crops [25,36,96].

SDG 10 is primarily a co-benefit, in relation to target 10.1 and 10.2 (empowerment and equalization) as developing decentralized bioenergy systems can improve job opportunities and economic opportunities within communities, especially those in low income, resource-dependent, and rural regions [48,56,97]. This can also reduce community dependency on large energy companies and improve energy independence. SDG 10 can also be a safeguard if the land is taken from marginalized populations and communities to supply large-scale bioenergy facilities, reinforcing already existing levels of inequality [18,98].

SDG 11 is a co-benefit as bioenergy systems can be part of sustainable community development plans and promote the efficient use of local resources. Doing so would lower overall levels of GHG emission and other pollutants and provide new job opportunities, especially in rural and remote communities (targets 11.3, 11.6) [53,56,99,100]. Bioenergy development could also improve the environmental footprint of cities if urban waste streams are used for bioenergy production (target 11.3) [68,69,101]. Given that piles of crop and forest harvest residues are commonly burnt in the open air, the use of these residues will improve local air quality (target 11.6) in rural regions, whose populations can also benefit through the provision of biomass to urban bioenergy systems, strengthening urban–rural linkages (target 11.a) [74,83,102–106].

3.1.3. SDGs with Low Likelihood of Being Linked to Biomass Supply for Bioenergy

SDG 4 is an enabler as increased access to education (target 4.1, 4.3) relevant to bioenergy and biomass supply may lead to increased development of bioenergy, particularly in areas where skills and knowledge were previously limited [18,21,23,93].

SDG 5 is a co-benefit of modern bioenergy development as clean cooking fuels can reduce health risks related to indoor smoke and can reduce the labor required for crop processing, or time spent collecting traditional wood fuels, tasks that are typically carried out by women [33,69,89,94]. Bioenergy projects could also improve women's access to land and resources if planning and governance are inclusive and/or done at a community scale [18,21].

SDG 14 may be a co-benefit or safeguard, depending on the impacts of the bioenergy supply chain on carbon emissions, which are tied to ocean acidification (targets 14.1, 14.3) [21,23]. If waste streams are also diverted for energy use, it could also reduce marine pollution (target 14.1) [69].

SDG 16 may work to enable bioenergy development if progress toward developing effective, inclusive, and transparent institutions and governance regimes is achieved (targets 16.6, 16.7, 16.8) [23,51]. The development of locally governed, community-scale bioenergy projects may lead to increase opportunities for participation in local decision-making [47,58,107].

SDG 17 may also enable bioenergy development and establishments of sustainable biomass supply chains through several targets related to finance, technology and capacity-building, and cross-sectoral partnerships [21,23,108,109].

3.2. *Case Study Analysis*

A total of 37 case studies from every continent were documented and analyzed with a range of feedstocks, supply chains, and end uses represented (Table S3). The majority of case studies examined projects that have been implemented (24), while five case studies examined proposed projects in various stages of planning, and nine case studies documented studies or trials on increasing the supply of biomass for energy. Most case studies were in North America and Europe (12 and 11 cases, respectively), with six in Africa, three each in Oceania and South America, and two in Asia. This distribution reflects the availability of documented case studies with suitable information, more so than the actual distribution of bioenergy projects across the globe.

Most implemented case studies use either forest (8/24) or agriculture residues (7/24), followed by waste (5/24) and energy crops (4/24) and produce heat as the primary output (17/24), consistent with bioenergy end uses globally. Heat end uses include space and water heating for individual buildings, cooking, process heat for food or wood processing, and district energy. Other implemented case studies include five where electricity is the primary output, three of which use biogas produced from waste sources to produce electricity, one that uses biomass from an energy crop, and another where wood pellets are exported from the US to Europe for large-scale electricity production. Liquid biofuels for transportation are produced as the primary output in two of the implemented case studies, from energy crops (sugarcane) and from the conversion of waste-generated biogas.

The majority of studied and proposed (non-implemented) case studies looked at production of cellulosic energy crops for biofuel production in North America (8/13), though often the primary purpose of the studied energy crops would be to provide ecosystem services related to non-energy SDGs. This is reflected in the fact that three of the energy crop case studies do not have a specified end-use. Other non-implemented case studies looked mostly at the use of agriculture residues for bioenergy (4/13) in Asia, Europe, and Africa, with one looking at supplying forest residues to a liquid biofuel facility in North America. A brief description of each case study along with an overview of the documented contribution of case studies on SDGs for each project, status, continent, biomass supply chain type, and end-use for each is provided in the supplementary material (Table S3).

Case Studies and Contribution to SDGs

The contributions to SDGs identified in the case studies were either supported by a quantitative assessment or qualitatively described. Quantitative evidence was only provided for 40% of the contributions recorded, through a variety of assessment methods and indicators, with original authors relying on observations or other qualitative evidence to demonstrate the existence of a majority of contributions (60%). The most commonly used indicators were: increase in income (SDG 2), reduced loads or concentration in pollutants (SDG 6), renewable energy supply (SDG 7), job creation (SDG 8), reduction in GHG emissions (SDG 9), and amount of waste or residues re-directed to bioenergy (SDG 12). However, even for those SDGs, only about half of the interactions were quantified (Figure 1).

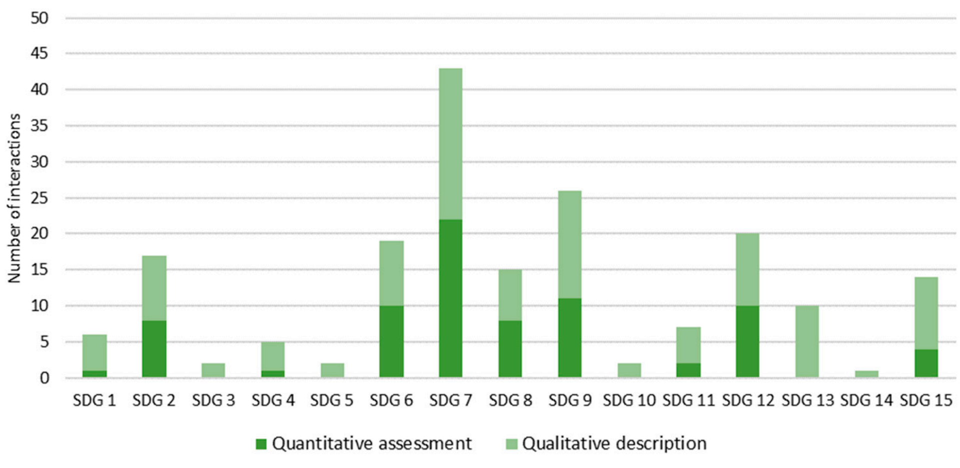

Figure 1. Evaluation of interactions between biomass supply for bioenergy and SDGs in case studies.

Figure 2a provides a visualization of the contributions of case studies to the SDGs. By default, all bioenergy case studies contributed to SDG 7, found at the center of Figure 2a. A total of 22 cases contributed positively to SDG 8, through targets related to job creation and resource use efficiency and SDG 9, through CO_2 emission intensity. Furthermore, 18 cases contributed to SDG 12, through resource use efficiency (any case related to target 8.4, also related to 12.2 and vice-versa) followed by 16 cases to SDG 2, through targets related to small farm income and agricultural productivity. Between 7 and 13 cases contributed to SDGs 6, 11, 13, and 15, while all other SDGs were related to fewer than five of the documented bioenergy case studies.

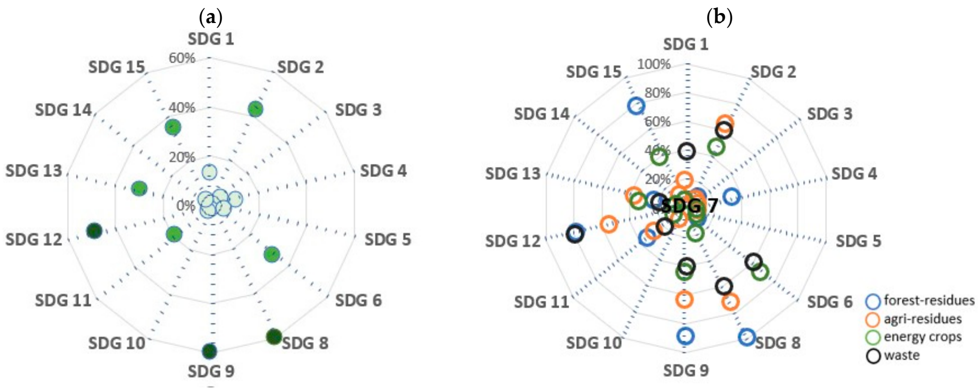

Figure 2. Percentage of (**a**) total cases contributing to each SDG and (**b**) cases by biomass supply chain type contributing to SDGs.

Results were analyzed to see if generalizations could be made as to the relationships with SDGs for 1) implemented versus planned or studied cases; 2) case studies in different continents; 3) different biomass supply chain types; or 4) different end uses. The most obvious differences in the contributions to SDGs were related to different biomass supply chain types, as shown in Figure 2b.

There were no obvious differences between the end-use type (heat, electricity, or transportation) when contributing to progress towards a SDG, suggesting that while some contributions are related to energy generation (see Section 3.1), those are generally not influenced by the biomass supply chain type. Differences between case studies that had been implemented or not were mostly tied to biomass supply chain types represented in each group (i.e., most non-food energy crop cases were not implemented). Biomass supply chain type was predominately the most significant indicator regarding potential contributions to specific SDGs, with geographic contributions to the SDGs depending mostly on the biomass supply chains present in the region. However, some geographic differences in contributions to the SDGs are worth noting, such as projects in rural and low-income farming communities were most likely to contribute to SDG 1; projects in Asia, Europe, and North America more likely to contribute to SDG9 through emissions reductions; and projects in Africa related to alternative cooking fuels were more likely to contribute to SDGs 3, 5, and/or 10. A link with SDG 4 was recorded in a few case studies in North America, and one in Africa, where training was provided to install and operate the bioenergy systems and supply biomass in a rural community. These differences, and the varying contributions to the SDGs by biomass supply type, are examined further in the discussion.

4. Discussion

Relationships between bioenergy (deployed for target 7.2) and other SDG targets, as identified in both the scoring exercise and case studies, are summarized in Figure 3. Light-colored bars beneath each supply chain in the figure represent relationships with SDGs that are a result of the deployment of new bioenergy generation, regardless of biomass source. The scoring exercise demonstrated that the SDGs most likely to be linked to bioenergy end-use are primarily goal related to social equity, health, and education. These include SDGs 1, 3, 4, 5, and 10 and are often advanced through improving access to energy and modernizing energy systems for heating, cooking, and electricity.

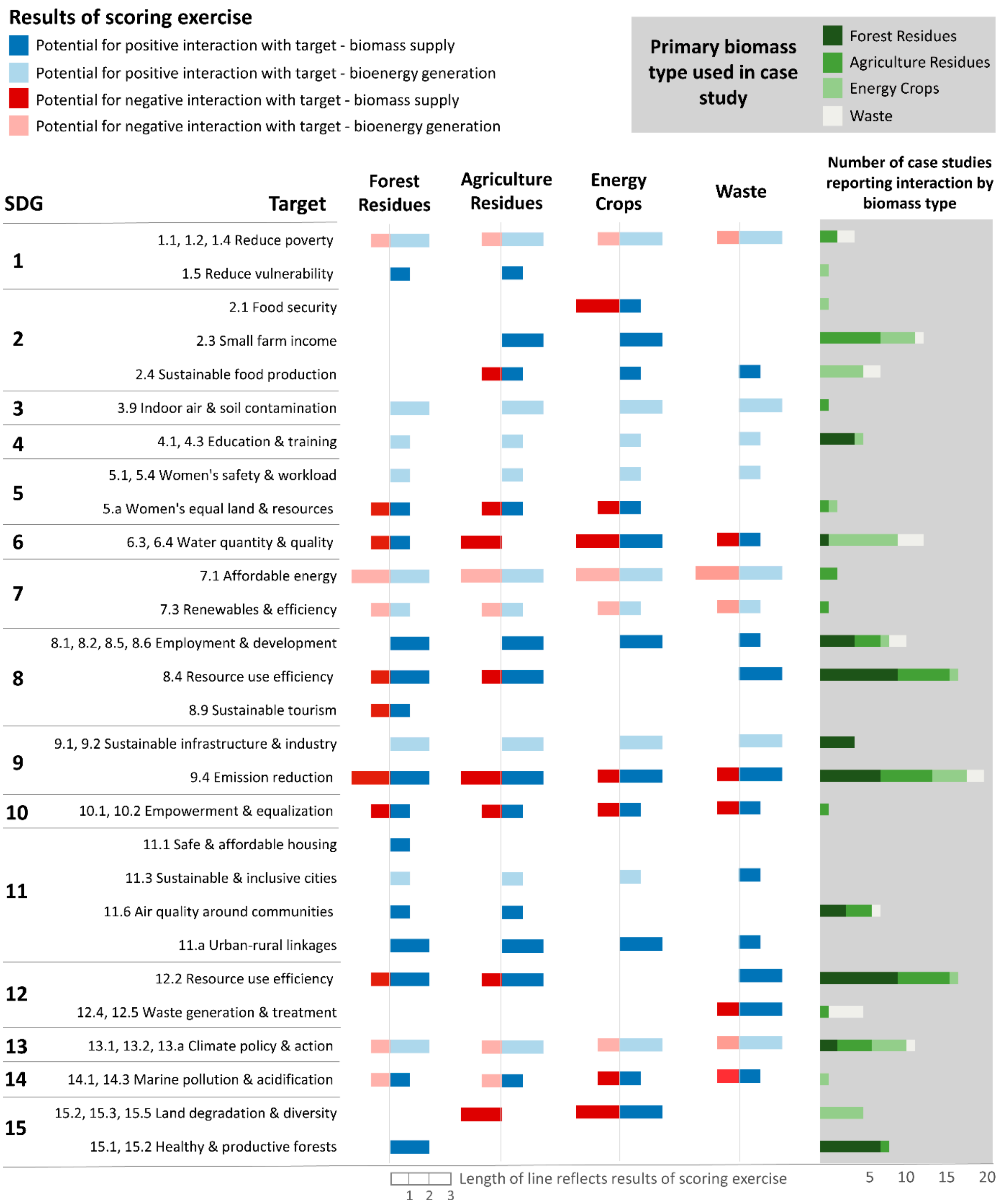

Figure 3. Relationships between biomass supply for bioenergy in pursuit of target 7.2 and SDG targets.

In the reviewed case studies, only a few, namely, those in rural and low-income communities, contributed to SDGs 1, 3, 4, 5, and 10. For example in case 1[1], a large farm in rural China supplies biogas produced from chicken manure to rural, low-income households surrounding the farm for free, hence providing access to a convenient, clean burning fuel that was not available previously (target 1.4). In case 32, small-scale combined heat and power (CHP) units, powered by crop residues, provide small farmers with access to power

[1] Refer to Table S3 in Supplementary Material for all case study numbers and descriptions.

(target 1.4) to dry and preserve their crops. Cases 30 and 36 qualitatively indicated a reduction in poverty rates (target 1.1) locally, and case 36 indicated an increase in income for lower-income households (target 10.1). Only cases 36 and 37 demonstrated a contribution to target 3.9 (indoor air quality), through improving cookstoves and transitioning to cleaner biofuels.

While these examples are only the ones where contributions were recorded, it is likely that other case studies indirectly contribute to targets 1.1, 10.1, and 3.9 but were either not the focus of the case study or perhaps were more difficult to observe than other contributions, and were therefore not documented. Similarly, there were no cases that specified a contribution to target 5.4 (related to reducing unpaid domestic work), though indirect contributions are likely for some, including the examples above, as it is predominantly women that farm and complete unpaid household labor in many rural communities. The two cases (34, 36) that indicated a link to SDG 5, did so through target 5.a which is related to access to land and resources, making it inherently tied to biomass supply. In the cases that indicated a contribution to target 4.3 (18, 22–24, 34), which encompasses participation in informal training, locals took part in training programs to learn to operate bioenergy equipment. In some cases, training was also provided on various aspects of biomass procurement or farming practices.

The scoring exercise found that bioenergy could negatively impact progress towards SDGs 1, 3, 4, 5, and 10 as bioenergy projects may centralize control over supply chains and bioenergy generation, or increase energy prices relative to alternatives. These negative impacts, however, were not documented for any of the case studies as these bioenergy projects were generally planned and implemented locally and at a scale commensurate with local resource availability and energy requirements.

The scoring exercise also found that bioenergy can either improve access to affordable clean energy (target 7.1) or restrict access to energy because of higher costs, depending on how and where it is implemented. Four cases in Africa (cases 32, 33, 36, 37) demonstrated improved accessibility to clean energy (target 7.3), specifically in rural or remote communities. Where small-scale bioenergy systems produce heat or power (or both) from low-cost biomass, they can reduce high energy costs that are associated with importing fuels, though this was not an impact recorded in case studies. It is also possible that the implementation of bioenergy may restrict access to clean energy through higher price points, depending on how and where it is implemented. For example, several countries have implemented blending targets for biofuels, which are typically more expensive to produce than fossil fuels and require large amounts of biomass [110]. Measures should be put in place to ensure that citizens, specifically low-income, are not disproportionately affected as countries increase reliance on bioenergy to reach climate change targets and that the procurement of biomass for these biofuels does not negatively affect small-scale farmers or forest operators.

Most other relationships with SDG targets (e.g., SDGs 2, 6, 8, 9, 11, 12, 15), documented both in the literature and the case studies, are related to the supply of different types of biomass as opposed to the generation of bioenergy. Figure 3 clearly demonstrates that many of the documented contributions of case studies to SDG targets are in fact linked to the biomass supply chains, not the energy generation system itself, suggesting that the relationships exist regardless of the end-use of the biomass.

4.1. Relationships between Biomass Supply Chains and SDGs

Unlike other renewable energy technologies fueled by wind, sun, geothermal energy, or moving water, bioenergy systems require procurement of varying amounts of sustainably sourced biomass to generate energy. The labor intensity of biomass procurement generates significant employment and economic development opportunities (especially in rural areas and low-income communities). Biomass production can be integrated within existing farming and forestry operations to improve ecosystem function, enhance the sustainability of farming and forestry practices, and improve waste management. Some targets related to the supply of biomass for bioenergy are likely to be advanced regardless of the type of biomass used, while others are tied specifically to certain biomass supply chains.

The scoring exercise, for example, found that SDG 8, target 8.5 was likely to be directly linked to biomass supply for bioenergy as jobs are likely to be created through the collection, processing, and transportation of biomass for bioenergy. The case studies reviewed support this finding, as 10 of the 37 cases recorded a contribution to target 8.5. Cases studying energy crops were least likely to report an impact on employment, but most of these cases focused on the potential impacts of integrating energy crops with farming practices and systems and, therefore, did not discuss employment opportunities. However, it is likely that energy crop supply chains would still result in employment opportunities and/or rural development as increasing crop production would result in increased labor requirements.

In a number of the cases, bioenergy projects in towns or urban centers were fueled with biomass from rural areas, strengthening links between urban and rural areas (target 11.a), however, this was not specifically documented in any case.

The scoring exercise found a strong link between bioenergy and SDG 9, specifically target 9.4 (upgrade infrastructure and retrofit industries to make them sustainable) linked to emission reduction.[2,3] This is because bioenergy generation is derived from biomass, and, therefore, overall emissions reductions from bioenergy systems depend significantly on where and how biomass is sourced.

4.1.1. Contributions of Forest Biomass Supply to SDGs

Typically, forest biomass is sourced from forests that are sustainably managed for the production of saw and pulp logs, within forest management frameworks that include safeguards to ensure provision of other ecosystem services is maintained (e.g., water purification, soil stabilization, or biodiversity conservation). Within this system, stems that meet quality requirements are used to produce long-lived, carbon-storing building materials, such as lumber and wood panels, while residues from forest harvest and management operations and wood processing are used for bioenergy.

All forest biomass case studies reviewed used sustainably sourced residues. Seven cases (8, 20–23, 25, 37) sourced forest biomass sustainably while improving forest management practices (target 15.2), including two examples of large-scale supply chains in North America (case 20) and Europe (case 8), through which well over a million tonnes of biomass is sourced annually. A market for biomass can enable improved forest management techniques such as thinning and stand improvement cuts that improve stand quality (increasing the amount of wood suitable for solid wood products), increase growth rates and, therefore, carbon sequestration, and reduce losses to wildfires and insects. Seven cases (8, 20–23, 25, 37) using forest biomass resulted in improved forest management practices (target 15.2), which in some cases was a primary driver for the bioenergy project. There are still concerns over the negative environmental and climate impacts of forest biomass supply for bioenergy, even when sourced from residues; however, these concerns are generally rooted in the misconception that whole forest stands are primarily harvested for energy [63].

The use of forest and wood-based product residues for bioenergy also improves resource use efficiency, particularly if the residues were previously a waste material. The scoring exercise found a strong link to SDGs 8 and 12, through targets 8.4 and 12.2, which focus on the material footprint of countries. Using forest biomass sourced from residue sources for energy reduces the need for fossil fuel extraction, resulting in an overall smaller material footprint. This contribution was documented for all nine forest bioenergy case studies. Local improvements in air quality were also recorded by three case studies (5, 8, 22) in regions where the burning of harvest residue or 'slash' piles at the roadside was com-

[2] The indicator specified for target 9.4 within the framework is "CO_2 emission per unit of value added".

[3] There is no similar indicator for SDG 13, so any contribution to emission reductions is recorded under SDG 9. A relationship with SDG 13 was recorded for case studies that were supported by programs or funding related to climate change or in some cases informed policy on land management or led to the implementation of climate-related policy.

mon practice. By instead using these residues for energy, the particulate matter emissions produced by open-air burning were reduced (target 11.6).

Deployment of bioenergy as a low carbon energy source has been debated due to concerns over the 'carbon debt' (the lag between when carbon is emitted and the time it takes for the forest to regrow), which are most prevalent for forest biomass supply chains. However, as outlined above, use of residues (from processing, management, and harvest), combined with a landscape approach to carbon modeling (including consideration of carbon stored in solid wood, reduction of fire and pests, and improved growth rates due to stand improvement cuts) can address this and significantly reduce the 'payback time'. When combined with carbon storage, negative emissions or carbon sequestration can be achieved, contributing to target 9.4 [63]. Emission reductions were recorded for all but one forest bioenergy case study.

4.1.2. Contributions of Agriculture Residue Supply to SDGs

Agriculture residues used for energy production generally fall into two categories: 1) crop residues and 2) food processing residues. The latter must be managed if not used for energy, similar to wood processing residues. Such use reduces the need to landfill or otherwise dispose of the residue stream (target 12.4—sustainable waste management) and improves resource use efficiency (targets 8.4 and 12.2). These were the only biomass supply-related contribution to SDGs recorded for cases using food processing residues. For example, case 10 uses residues from the wine industry for bioenergy production and noted a positive contribution to target 12.4, while cases 10, 11, 35, and 36 recorded a positive contribution to target 12.2.

Increased removal of crop residues, on the other hand, has the potential to reduce the nutrient or carbon content in the soil if the removal rate is too high and not enough organic material is returned to the soil [31,32]. This may also reduce the capacity for water retention in the soil and lead to increased runoff and soil erosion, potentially affecting local waterways and increasing the need for irrigation [29,31]. Carbon emissions may increase as a result of unsustainable residue removal if the need for synthetic fertilizers increases, or if soil carbon content is significantly reduced. Effects of increased removal vary depending on local climate, soil type, topology, and other factors and should be tested locally before increasing removals of residues [29,31].

Often, at least a portion of crop residues is already removed from fields and has become a problematic 'waste' stream that must be dealt with by farmers [32]. Open-air burning of crop residues is a common and accepted practice in many regions that can be reduced if residues are used for energy. Reduced open-air burning may improve local air quality (target 11.6), an impact that was documented for three case studies (cases 2, 6, 7) using crop residues. In all case studies that use crop residues (cases 2, 6, 7, 9, 12, 32, 33), residues were removed from fields and burnt, landfilled, or otherwise disposed prior to use for bioenergy. Therefore, any negative impacts related to unsustainable residue removal rates avoided and reductions in carbon emissions (target 9.4) may be achieved. The case studies also demonstrate that the additional revenue generated from agriculture residues can have a meaningful positive impact on incomes for small farmers (target 2.3), as was documented in seven case studies cases in which agriculture residues were used as a bioenergy feedstock.

4.1.3. Contributions of Energy Crops to SDGs

Due to concerns around targets 2.1 and 2.4 highlighted in the scoring exercise, it is critical that bioenergy crops are integrated with traditional farming systems in a way that does not negatively impact food production or exacerbate freshwater scarcity, but instead enhances ecosystem services and maximizes positive impacts on several SDGs. Integrated or co-productive farming systems, such as double cropping with annual grasses (case 3), alley crops (case 26), intercropping (cases 16, 17, 34), and buffer strips (case 18) are being explored, and in some cases (3, 34) implemented, to produce bioenergy crops alongside food crops. Integration of energy crops can lead to enhanced ecosystem function by improving soil or water quality (targets 2.4 and 6.3, respectively), reducing runoff and erosion (targets 2.4, 6.4), or increasing soil carbon storage (target 9.4), among other benefits. The additional crop also diversifies the revenue stream of small farmers, increasing profits (target 2.3) and hedging against crop losses (target 1.5,13.1), which may increase with climate change.

Woody energy crops, such as willows or poplars, can be planted to filter wastewater (target 6.3), or restore degraded land (target 15.3), with the added benefit of providing biomass for energy, as in cases 4 and 27, respectively. It is critical that a systems approach is taken for planning and monitoring these integrated systems on a case-by-case basis to avoid any negative impacts on local water availability or soil quality.

Changes in carbon emissions due to the establishment of energy crops is dependent primarily on the previous state of the land on which the crop is established [36,66,67]. Energy crops that are established on degraded land, or that replace (or are integrated with) annual crops, are likely to act as a carbon sink and reduce the concentration of CO_2 in the atmosphere. If energy crops replace natural landscapes, on the other hand, carbon may be released, and biodiversity may also be negatively affected. Cases 3, 14, 18, and 19 were the only energy crop case studies for which a contribution to target 9.4 (reduce CO_2 intensity) was recorded. Most energy crop cases have not yet been implemented and were being studied to provide other services, in addition to energy, so emission reduction potential may not yet be clear, or was not a priority.

While most new bioenergy generation will be derived from residue streams and non-food crops [9], it is important to recognize that the majority of biofuels produced currently are from food crops [110]. Efforts are being made to improve the sustainability of crop production (e.g., sugarcane, corn) used for ethanol through the production of energy from residues (e.g., case 31) or improving water use efficiency (e.g., case 29). Adaptive governance strategies can also help to ensure that biomass will not compete with scarce food resources, for example, through flexible fuel standards to vary biofuel demand based on available resources [111].

4.1.4. Contributions of Waste Biomass Supply to SDGs

Similar to the use of food and wood processing residues, few negative impacts related to waste biomass supply chains are expected. Possible negative contributions to targets 6.3 (water quality), 9.4 (reduce CO2 intensity), and 12.5 (waste management) for waste bioenergy systems are related to the anaerobic digestion process commonly used to generate energy from organic waste streams. Biogas (methane) leaks are possible if the system is not properly designed [70,71], and digestate (a byproduct of anaerobic digestion) can pollute local environments if not properly dealt with [34,69].

All bioenergy case studies converted waste streams to biogas using anaerobic digestion. Three cases (1, 28, 30) solely used on-farm manure as the feedstock, one (case 31) used vinasse produced as a by-product of sugarcane conversion to ethanol, and another (case 13) used a combination of manure from local farms and a liquid byproduct stream from a grass biorefinery. In some cases (cases 1, 28, 30), the remaining digestate was spread on nearby farm fields, reducing the need for fertilizer (target 2.4). Testing was done in case 1 to ensure digestate application to farm fields did not pollute local water bodies. In cases 1 and 31, a positive contribution to target 6.3 was documented as removal of waste streams from the land prevented run-off or leaching of nutrients into groundwater.

Diversion of waste streams for bioenergy was noted by four cases (cases 1, 28, 30, 31) to contribute positively to target 12.4, which aims to achieve environmentally sound management of all wastes throughout their life cycle. A contribution to target 12.2 (resource use efficiency, also 8.4) was recorded for case 13 in which a biorefining by-product stream was converted to biogas. It could be argued that all cases contribute to both targets 12.2 and 12.4, as all result in the more environmentally sound management of waste streams and improve resource use efficiency. Similarly, contributions to SDG 9 were found (cases 1, 28, and 31) as GHG emissions reductions were associated with the implementation of these bioenergy systems. These contributions were likely the same for cases 13 and 30 but were not recorded.

4.2. SDGs as a Normative Framework for Biomass Supply Sustainability: Recommendations and Future Work

This study informs how SDGs can be used as a normative framework to guide the implementation of sustainable biomass supply chains for bioenergy generation, but also the broader bioeconomy. Recommendations for key stakeholders and topics for future work are proposed below.

Developers of sustainability assessment frameworks can re-visit their list of criteria and indicators (typically structured around the three pillars of sustainable development) to ensure comprehensive coverage of the SDG targets identified in the scoring tables (Tables 2–8 and Tables S1 and S2) in their own frameworks. In addition, contributions to the SDGs in the case studies reviewed were predominately documented using qualitative evidence. Quantitative assessment of bioenergy systems and their biomass supply chains could be facilitated if criteria and indicators in existing frameworks were mapped against the SDGs, in order to avoid gaps (i.e., relevant SDG targets with no associated indicators) or duplication (i.e., the same indicator being repeated under several SDG targets) as much as possible. Such a mapping exercise was initiated by GBEP [85] but has not yet been transposed in the GSI Implementation Guide [15]. The case studies also demonstrated that the most relevant SDGs and targets varied, at least in part, between biomass supply chain types. As a consequence, priority criteria and indicators could be identified in assessment frameworks for main supply chains, namely to support streamlined evaluations. Overall, improving tools to assist in the quantitative reporting, and evaluation, of bioenergy systems and their supply chains will improve decision-making regarding bioenergy's sustainability and public policy.

Bioenergy project developers and biomass suppliers can refer to the SDG targets identified in the scoring exercise and the case study analysis as a sustainability checklist when projects are initiated. The results presented here can also be used once the systems are in operation to prioritize key indicators for which quantitative and verifiable data need to be collected, analyzed, and reported. While comprehensive assessment of multiple indicators, which each rely on complex methods can be suitable for research projects, it is usually not feasible for industrial or community projects to perform this level of monitoring. However, using the SDGs can help foster a mutual understanding of issues that should be prioritized among the different actors involved during the implementation of bioenergy systems and their supply chains. The large majority of relationships identified in this analysis apply to biomass supply chains regardless of what feedstocks are used for and can thus inform the development of a broader bioeconomy beyond bioenergy projects.

Policymakers are also increasingly being expected to implement bioenergy policies, and all energy policies for that matter, that address the environmental, social, and economic need and, therefore, fully contribute to the implementation of the 2030 Agenda for Sustainable Development. The findings presented in this article, namely, on the diverse nature of relationships between biomass supply chains and SDGs, can support the elaboration of well-integrated policies. For example, *drivers* for biomass supply resulting from incentives or obligations should be balanced between bioenergy and other competing uses. Existing regulatory frameworks should also be assessed and augmented to ensure they provide the necessary *safeguards* to risks from biomass supply expansion. The value of *co-benefits* should be recognized, financially or otherwise, so that the adoption of best practices by economic actors is supported in a consequent manner. Lastly, governments are in a unique position to provide *enablers* with benefits to diffuse for individual actors of the supply chain to implement them. Of course, this requires policymakers to go beyond sectoral silos so that future policies, strategies, and regulations provide a frame for bioenergy projects to contribute to multiple domestic priorities.

5. Conclusions

Sustainably sourced biomass for bioenergy generation will be essential as it is increasingly relied upon to support sustainable development. While biomass supply for bioenergy generation directly contributes to SDG 7, it can also have meaningful contributions to the other SDGs. At least half of the 37 case studies reviewed contributed towards SDGs 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), and 12 (Responsible Production and Consumption), with differences in contributions across supply chains. Some supply chains were more likely to impact some SDGs more than others such as agricultural supply chains (i.e., energy crops and residues) that are more likely to impact SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation), with waste and forest supply chains more likely to impact SDG 15 (Life on Land). Biomass supply for bioenergy generation was also found to indirectly contribute towards socioeconomic focused SDGs such as SDGs 1 (No Poverty), 4 (Quality Education), 5 (Gender Inequality), and 10 (Reduced Inequalities). These findings can be applied to biomass supplied for non-energy uses as well and are relevant to key stakeholders in the bioeconomy. For example, mapping of existing indicator frameworks to the SDGs could advance with project-level reporting on progress forward SDGs, the SDG targets identified could be used as a 'sustainability checklist' by developers and biomass suppliers to build a strong rationale for bioenergy and influence partners to get on board; or the likelihood and nature of interactions identified can support the elaboration of a comprehensive suite of policies.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-445X/10/2/181/s1, Table S1: Scoring for SDGs with a moderate likelihood of interaction with biomass supply chains for modern bioenergy; Table S2. Scoring for SDGs with a low likelihood of interaction with biomass supply chains; Table S3: Case study summary.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data used is a subset of a larger database for which parts are still being reviewed and that will be made available as part of an IEA Bioenergy report later in 2021.

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Appendix A

Table A1. Sustainable development goals.

Sustainable Development Goal (SDG)	Descriptions
1. No Poverty	End poverty in all its forms everywhere
2. Zero Hunger	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
3. Good Health and Well-being	Ensure healthy lives and promote well-being for all at all ages
4. Quality Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5. Gender Equality	Achieve gender equality and empower all women and girls
6. Clean Water and Sanitation	Ensure availability and sustainable management of water, sanitation for all
7. Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
8. Decent Work and Economic Growth	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
9. Industry, Innovation, and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
10. Reduced Inequalities	Reduce inequality within and among countries
11. Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient, and sustainable
12. Responsible Consumption and Production	Ensure sustainable consumption and production patterns
13. Climate Action	Take urgent action to combat climate change and its impacts
14. Life Below Water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
15. Life on Land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16. Peace, Justice, and Strong Institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels
17. Partnerships for the Goals	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

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