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Sustainability criteria for bioenergy systems: results from an expert survey

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ABSTRACT

Environmental impacts associated with the use of fossil fuels, rising prices, potential limitations in supply and concerns about regional and national security are driving the development and use of biomass for bioenergy, biofuels and bioproducts. However, the use of biomass does not automatically imply that its production, conversion and use are sustainable. In order to operationalize sustainability assessments of biomass systems, it is crucial to identify critical criteria, but keep their number and measurement at a manageable level. The selection of these criteria can vary depending on individual's expertise, geographical region where they work, and spatial scale they are focused on. No clear consensus has yet emerged on what experts consider as critical indicators of sustainability. Objectives of this paper were to analyze how key experts perceive the 35 sustainability criteria for bioenergy found in emerging sustainability assessment frameworks and to identify levels of agreement and uncertainty. Experts were asked to rate the criteria for attributes of relevance, practicality, reliability, and importance.

Perceptions of the importance of the 35 criteria varied among the experts surveyed. Only two criteria, energy balance and greenhouse gas balance, were perceived as critical by more than half of the respondents. Social criteria and locally applied criteria were generally ranked low for all four attributes. Seven of the 12 criteria scored as most important focused on environmental issues, four were social and only one was economic. Of the 12 most important criteria, seven were ranked low in practicality and reliability indicating that mechanisms to assess a number of important criteria need to be developed. The spatial scale the experts worked at and their profession explained most of the differences in importance ranking between experts, while regional focus had minimal effect. Criteria that were ranked low for importance, were characterized by a lack of consensus, suggesting the need for further debate regarding their inclusion in sustainability assessments.

Outcomes of the survey provide a foundation for further discussions and development of sustainability assessments for bioenergy systems and may also provide a basis for assessing individual bioenergy projects within their specific geographic, ecological, societal, and technological context and scale.

1. Introduction

Environmental impacts associated with the use of fossil fuels, rising prices, potential limitations in supply and concerns about regional and national security are driving the development and use of biomass for bioenergy, biofuels and bioproducts. At the same time, lower biomass production costs in developing countries are increasingly being linked with the energy demand in industrialized nations, often driven by an effort to reduce carbon emissions from the transport sector (e.g. Yacobucci [1] for the US, European Commission [2], or Fehrenbach et al. [3] for Germany). As a result, international biofuels trade is beginning to expand rapidly (e.g. Junginger et al. [4]).

The use of bioenergy does not automatically imply that its production, conversion and distribution are sustainable. Identifying what is sustainable is difficult because sustainability as a social value is by nature controversial [5]. For instance, some people value the social, economic, and ecological factors of sustainability equally, while others support the view of a nested components of sustainability, stressing that sustainability can only be achieved when its social and economic factors do not violate ecological limits (the biophysical view of sustainability, [6]). Since the multiple perspectives encompassed in the concept of sustainability are based on normative values, the concept requires specific measurements.

The network of interconnected supply chains associated with internationally traded biomass or biofuels makes ensuring

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sustainability more challenging than biomass that is produced and used locally, but the assessment framework could be similar at either scale. A sustainability assessment of bioenergy systems needs to include the whole production cycle including biomass production and transportation, conversion technology, and energy allocation. In order to operationalize sustainability assessments of bioenergy systems, it is crucial to identify critical criteria, keep their numbers at a manageable level, and remain responsive to the values expressed by stakeholders at the local level.

Certification is one mechanism for conducting criteria based assessments and is currently driven by international and national efforts related to global biomass trade such as Roundtable on Sustainable Biofuels [7] Lausanne, or the Cramer Commission [8]. While there has been a great deal of beneficial discussion about sustainability through these efforts and other forums (for an overview see e.g. van Dam et al. [9] or Vis et al. [10]), there are only a few examples of certified bioenergy systems that have been hypothesized or put in practice (e.g. Smeets et al. [11]). No clear consensus amongst bioenergy experts and other stakeholders has yet emerged on which indicators are critical and which framework should become standard practice. This lack of agreement on sustainability for bioenergy systems is not only prevalent when dealing with global biomass trade. Consent on which sustainability criteria are relevant, practical, reliable, and important is also low for bioenergy applications in smaller scales (e.g. McCormick and Kåberger [12]). While specific criteria can be quantified and measured, such as carbon and energy cycles of liquid biofuels, using tools such as life cycle analysis (e.g. Wang [13]), other sustainability criteria (e.g. local participation or food vs. fuel) cannot be measured by such tools. The measurement of these criteria is often hotly debated while even their significance is disputed amongst experts.

A holistic sustainability assessment framework for bioenergy systems that would recognize those individual sustainability criteria and their relationships with each other is lacking at either the international or local scale. Current efforts to assess sustainability based on the social-economic-ecological concept are still somewhat ad hoc in their approach to identify the criteria we need to appraise each of the three factors. The use of an integrated approach such as a materials and energy flow systems illustration provides a basis to clearly identify criteria for inclusion in a sustainability assessment that more comprehensively reflect the full system and the values of the stakeholders [14].

1.1. Goals and objectives

To contribute to the ongoing debate about sustainability, we wanted to identify areas of agreement and uncertainty among international experts about the importance, relevance, practicality, and reliability of sustainability criteria for bioenergy systems that are currently being discussed around the world. Similar survey efforts are being pursued on national levels (e.g. Wellisch [15], performed an expert survey focusing on Canada) but to date, none have measured and analyzed consensus at an international level.

The specific study objectives were:

- Analyze how currently discussed sustainability criteria are perceived by bioenergy experts around the world in relation to their relevance, practicality, reliability and importance.
- Identify levels of agreement and uncertainty amongst experts on criteria.
- Explore which frameworks are preferred by bioenergy experts for sustainability assessments of bioenergy systems.

2. Methods

2.1. Study population

We identified a population of 137 bioenergy experts as key participants in the current bioenergy debate with specific attention to a range of experience in regions, types of bioenergy systems, scale of operations, and professions. Experts were identified through the bioenergy literature, conference participation lists, and members of international bioenergy organizations such as the International Energy Agency (IEA) Bioenergy. Each expert was identified as having a considerable influence in the discussion of sustainability assessment of bioenergy systems.

2.2. Survey design

2.2.1. Respondent demographics

Respondents were asked to provide information about their professional background, geographical expertise, the scale of bioenergy projects they are familiar with, and their expertise in certification. This information was used to assess if there were differences of opinion between groups of respondents based on these characteristics.

2.2.2. Criteria identification and rating

Through a literature review, we identified 35 sustainability criteria that are regularly included in discussions about bioenergy (see Appendix 1). Sources included Cramer et al. [16], van Dam et al. [17], Fritsche et al. [18], Jürgens and Best [19], Lewandowski and Faaji [20], Modi et al. [21], Reijnders [22], Five Winds International [23], Smeets et al. [24], the Sustainable Bioenergy Wiki [25] of the Roundtable on Sustainable Biofuels (RSB) Lausanne, Upreti [26], and the World Energy Council [27]. The criteria that were identified were grouped into the broad categories of social (15 criteria), economic (four criteria) and environmental (16 criteria). Participants were asked to rate each of these 35 sustainability criteria on four attributes including relevance, practicality, reliability, and importance using the following definitions:

- **Relevance:** How relevant is the criterion to the concept of sustainable bioenergy systems? Does its assessment contribute to a better understanding of the sustainability of the bioenergy system?
- **Practicality:** Are there existing scales and/or measurement units? Are there measurable threshold values? How easily can data be obtained? Is measuring the indicator cost, time and/or resource effective?
- **Reliability:** How reliable is the result of assessing the criterion? Is there a high uncertainty attached to the criterion? Are results reproducible? How easily can consensus be achieved?
- **Importance:** How important is the criterion for assessing the sustainability of the bioenergy system? Is it critical, i.e. is it according to your opinion mandatory to include it in a sustainability assessment of bioenergy systems?

The criteria's relevance, practicality, and reliability were rated using the same scale (Low, Medium, High, No Opinion). Given the number of questions in the survey, a three point scale was chosen to use a simple yet easy response by respondents. This scale would not require extensive guidance while still being a good measurement covering the whole range while being mutually exclusive. The importance attribute was measured using a slightly different scale (Low, Medium, High, Critical, No Opinion) where 'critical' was meant to be chosen by respondents for a criterion which needs to be included in any bioenergy sustainability assessment.

Respondents were also given the opportunity to comment or add missing criteria and rate them in a special section of the survey.

2.2.3. Evaluation of assessment frameworks

In the last part of the survey, respondents evaluated five different frameworks for organizing criteria in sustainability assessments. The frameworks were rated using the following scale (No Opinion, Poor, Fair, Good, Very Good, Excellent) and respondents were asked to identify their preferred framework. Respondents also were given the opportunity to comment or add missing frameworks and rate them. The following sustainability assessment frameworks were included in the survey[1]:

- Social, economic, environmental; abbreviated in the following as *SEE*.
- Benefits, opportunities, costs, risks; abbreviated in the following as *BOCR*.
- Strengths, weaknesses, opportunities, threats; abbreviated in the following as *SWOT*.
- (Driving force), pressure, state, (impact), response; abbreviated in the following as *(D)PS(I)R*.
- Greenhouse gas balance, competition for land, biodiversity, economic prosperity, social well-being, environment based on Cramer et al. (2006); abbreviated in the following as *Cramer*.

2.3. Survey implementation

Participants received a survey and explanatory cover letter in May 2007 and a maximum of two follow up emails spaced 2 weeks apart to encourage participation. 46 individuals participated within the study time frame. A telephone follow up with 10% of those who did not participate revealed no significant differences from respondents and no one specifically refused for reasons other than workload and timing. As such, the results of this study represent the opinions of 46 key bioenergy experts from around the world.

2.4. Survey analysis

Results were analyzed using SPSS 16.0 and Microsoft Excel software. If respondents chose 'no opinion' for one item, the case was eliminated. As a means to compare rating between criteria but within attributes, an average rating was calculated for each criterion and attribute. Ratings were counted as Low = 1, Medium = 2, High = 3, Critical[2] = 4, and the resulting mean was taken as the average rating. The overall average rating for each attribute was calculated as well.

The homogeneity of respondents' ratings for each criterion was assessed using the standard deviation of counts within the response ratings as a 'consensus rating'. A high standard deviation indicates an uneven distribution of ratings across the scale with a tendency towards one rating. A low standard deviation indicates a more even distribution of ratings across the scale and therefore low consensus. Using the standard deviation as consensus rating was possible as there was no occurrence where criteria were rated on both extremes but little in the medium scale.

For further analysis, respondents were divided in groups according to their demographic characteristics. Groups were aggregated when necessary for analysis (results in those cases are so noted). Fisher's Exact Test [28] was used for small group responses to detect significant rating differences between groups of respondents based on contingency tables.

[1] The recently published RSB Version Zero [7] framework was not developed at the time of this study and could therefore not be incorporated.

[2] 'Critical' only applicable for attribute importance.

3. Results and discussion

3.1. Demographic characteristics of respondents

The majority of respondents had a professional focus on biomass production while the remainder were experts in bioenergy conversion technologies or general bioenergy research (Fig. 1). The representation of primary scales of operation was more evenly distributed, but the focus was a national scale. Respondents had experience in all continents except Antarctica, with Europe and North America most common. Most respondents worked for government agencies or in academia.

3.2. Criteria rating

Table 1 shows the average rating for each criterion on each of the four attributes (relevance, practicality, reliability, and importance) as rated by all 46 experts. Further analysis was based on these average ratings and, to better focus the discussion, the top third most important criteria as ranked by experts.

3.2.1. Differences in importance between social, economic, and environmental criteria

The 35 criteria included in the survey represented social, economic, environmental categories in a ratio of about 4:1:4 indicating the strong emphasis on social and environmental issues in the literature. However, the top third most important criteria as rated by experts in this study included a greater proportion of environmental criteria (7) followed by social (4) and economic (1). When looking at criteria by category, the environmental criteria were rated the highest in both importance and relevance, followed by economics, then social criteria. Economic criteria as a group were rated as most practical and reliable followed by environmental then social criteria. In summary, environmental criteria were rated as more important and relevant, and economic criteria as more reliable and practical while social criteria always rated the lowest.

The suggestion that social criteria are perceived as less important is further supported by the fact that eight out of the 12 criteria with the lowest average rating in importance are classified as social (see Table 1 and also Fig. 2). Even *employment generation* (no. 16), a criterion which can be categorized as social or economic criterion, and often discussed in sustainability forums (e.g. RSB 2008; IEA Bioenergy Tasks 29 and 40), consistently ranked in the middle third for all four attributes. One interpretation of these results is that many experts consider the biophysical as the ultimate limiting factors for sustainability. It may also be due to experts giving higher ratings to those areas they know best. Given that most respondents come from a biomass production background (Fig. 1), it is highly likely that they had biophysical science as their primary disciplinary strength. Sustainability assessments may therefore be improved by ensuring the breadth of disciplinary foundations of participants across appropriate biophysical and social sciences.

Another surprising observation was that the criterion *macroeconomic sustainability* (no. 18), which could indicate if a bioenergy system can be run profitably in absence of subsidies, was ranked in the bottom third for relevance, practicality, and importance. This notion could be interpreted as a general agreement that government support may be required and accepted, especially in the near term, to develop bioenergy systems to the point that they can be profitable on a macroeconomic level. It could also suggest that environmental issues are seen as more important than

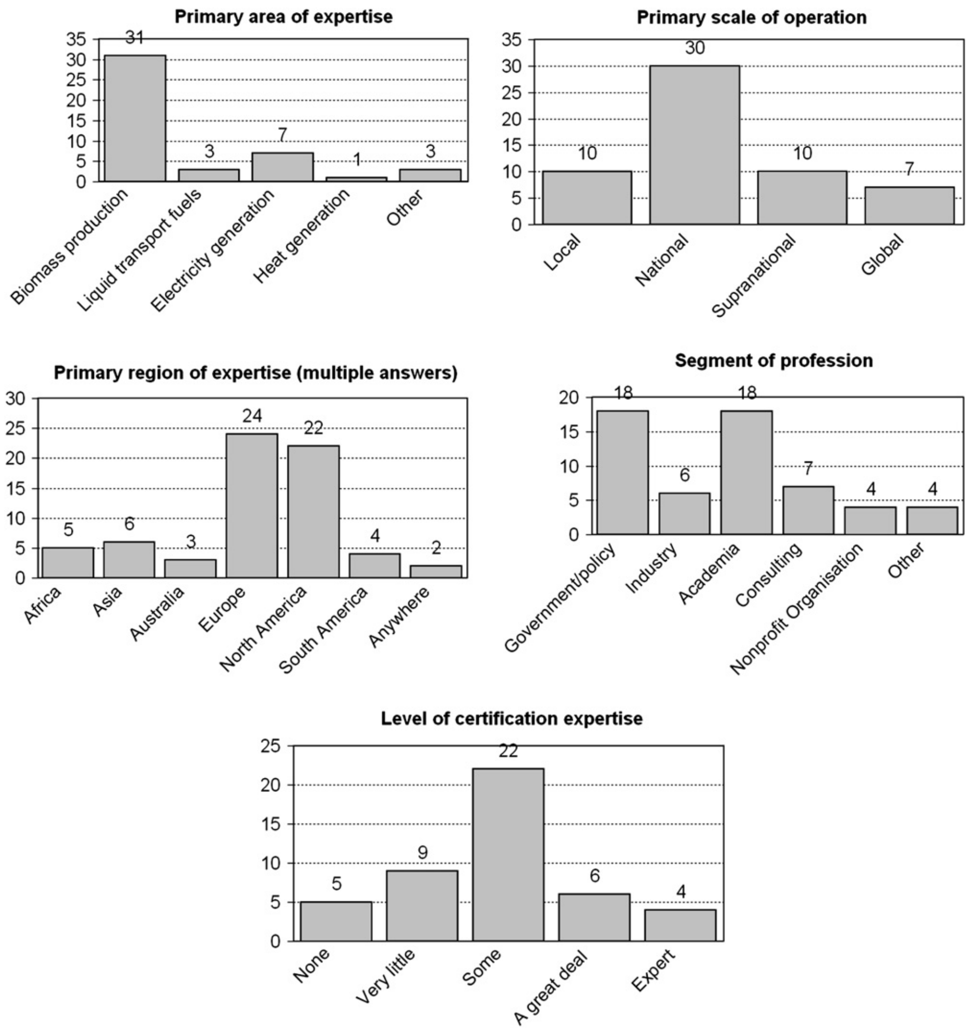

Fig. 1. Respondents' primary area of expertise scale of operation, segments of profession, and certification expertise.

macroeconomics and that support for more environmentally friendly sources of energy should be developed even if they are more costly.

3.2.2. Criteria importance ratings

3.2.2.1. Critical criteria. Each criterion was rated as critical (mandatory for all sustainability assessments) by at least one respondent (Fig. 2). However, only two criteria, *energy balance* (no. 21) and *greenhouse gas balance* (no. 34), were rated as critical by more than half of the respondents. This is an interesting outcome in light of the dispute on how 'net energy' balance should be considered in bioenergy systems and reflects the current controversial debate on the topic.[3] Ten of the 12 most important criteria (~top third) also lead the list of the most critical criteria (Fig. 2).

Looking at criteria ranked as critical or highly important gives a more unified picture. Over 75% of respondents rated the following eight criteria as critical or highly important: *energy balance* (no. 21), *greenhouse gas balance* (no. 34), *participation* (no. 4), *soil protection* (no. 30), *ecosystems protection* (no. 24), *water management* (no. 32), *natural resource efficiency* (no. 22), and *microeconomic sustainability* (no. 17). Ten criteria had fewer than 50% of the respondents rate them as critical or highly important, including eight social criteria (no. 5, no. 7, no. 9, no. 14, no. 6, no. 15, no. 10, no. 3), one environmental (*exotic species applications*, no. 27) and one economic (*macroeconomic sustainability*, no. 18). This finding may reflect a biophysical science foundation of most bioenergy experts.

3.2.2.2. Top third important criteria. The top third most important criteria determined using average scores for the complete sample (>2.9 of a possible 4, Table 2) included *compliance with laws* (no. 1), *food security* (no. 2), *participation* (no. 4), *monitoring of criteria performance* (no. 13), *microeconomic sustainability* (no. 17), *energy balance* (no. 21), *natural resource efficiency* (no. 22), *ecosystems protection* (no. 24), *soil protection* (no. 30), *water management* (no. 32), *waste management* (no. 33), and *greenhouse gas balance* (no. 34). Examining importance ratings by groups (profession, scale, region, and certification expertise) revealed that 24 of the 35 criterion were rated in the top third by at least one group and 11 criteria were not included in the top third criteria list for any of the groups. All groups had at least eight criteria in common with the top third of the complete sample, although not the same eight. Only two criteria were contained in all top thirds for all groups (*soil protection*, no. 30, and *greenhouse gas balance*, no. 34) suggesting a heterogeneous mix of opinions on importance of criteria.

[3] See e.g. Dale [37] for a position dismissing the importance of 'net energy' balance for biofuels, and Hall et al. [38] as an opposing view.

Table 1
Average ratings of criteria for all attributes, ranked by the importance rating.

Criterion no.	Criterion name	Nature of criterion	Relevance rating	Practicality rating	Reliability rating	Importance rating
34	Greenhouse gas balance	Environmental	2.84	2.33	2.17	3.55
21	Energy balance	Environmental	2.87	2.51	2.39	3.44
30	Soil protection	Environmental	2.85	2.23	2.07	3.27
4	Participation	Social	2.80	1.98	1.95	3.16
32	Water management	Environmental	2.74	2.12	2.00	3.14
22	Natural resource efficiency	Environmental	2.78	2.02	1.86	3.11
17	Microeconomic sustainability	Economic	2.74	2.46	2.30	3.10
1	Compliance with laws	Social	2.46	2.13	1.95	3.09
24	Ecosystems protection	Environmental	2.87	1.98	1.95	3.07
13	Monitoring of criteria performance	Social	2.73	2.12	2.02	3.02
2	Food security	Social	2.53	1.91	1.79	2.95
33	Waste management	Environmental	2.70	2.39	2.23	2.93
20	Adaptation capacity to environmental hazards and climate change	Environmental	2.63	2.05	1.80	2.90
26	Crop diversity	Environmental	2.48	2.10	1.95	2.86
8	Working conditions of workers	Social	2.65	2.27	1.98	2.83
12	Planning	Social	2.47	2.22	2.03	2.79
19	Economic stability	Economic	2.51	1.98	1.79	2.79
23	Species protection	Environmental	2.51	1.74	1.68	2.76
29	Use of chemicals, pest control, and fertilizer	Environmental	2.53	2.23	2.07	2.72
35	Potentially hazardous atmospheric emissions other than greenhouse gases	Environmental	2.57	2.26	2.17	2.72
16	Employment generation	Economic	2.51	2.33	2.15	2.69
11	Property rights and rights of use	Social	2.55	2.00	1.76	2.68
31	Land use change	Environmental	2.40	1.79	1.64	2.68
28	Use of genetically modified organisms	Environmental	2.44	2.07	1.85	2.64
25	Ecosystems connectivity	Environmental	2.44	1.91	1.71	2.57
7	Respect for human rights	Social	2.28	1.55	1.50	2.48
18	Macroeconomic sustainability	Economic	2.30	1.83	1.89	2.39
5	Cultural acceptability	Social	2.23	1.58	1.45	2.37
9	Respecting minorities	Social	2.20	1.62	1.45	2.35
27	Exotic species applications	Environmental	2.18	1.88	1.69	2.33
6	Social cohesion	Social	2.16	1.62	1.46	2.26
3	Land availability for other human activities than food production	Social	2.18	1.70	1.63	2.25
10	Standard of living	Social	2.14	1.77	1.67	2.14
15	Noise impacts	Social	2.00	2.05	2.02	2.10
14	Visual impacts	Social	2.02	1.81	1.55	1.98
Overall average rating			2.49	2.01	1.87	2.75
Consensus (std. deviation)			0.25	0.26	0.25	0.38

For criteria names and explanations see Appendix 1. A high average rating indicates a more relevant, practical, reliable, or important criterion. Average rating corresponded to 1, 2, or 3 (with 4 indicating 'critical' for the importance rating only).

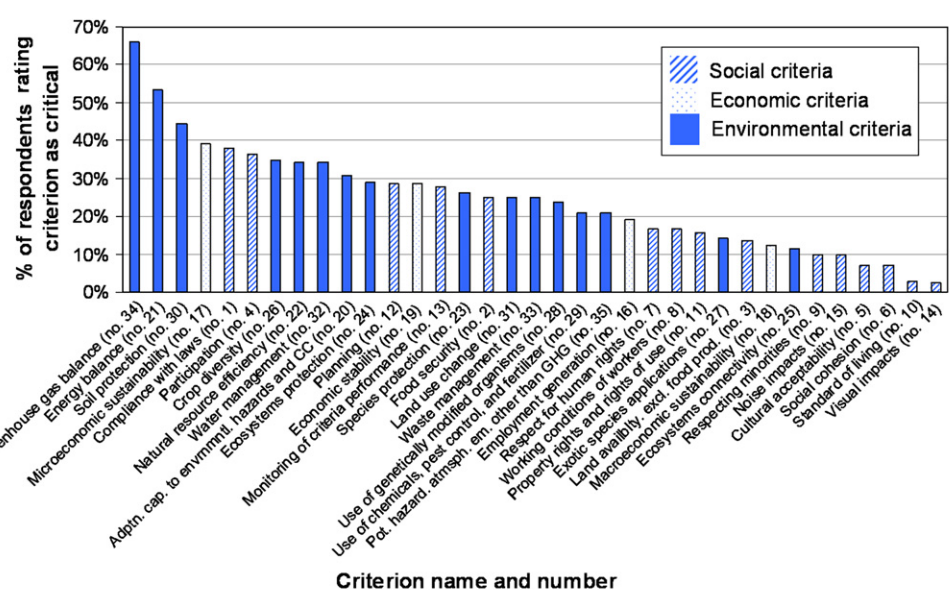

Fig. 2. Proportion of respondents rating a given criterion as critical ($N = 36–45$). For criteria names and descriptions see Table 1 and Appendix 1.

Table 2
Top third criteria according to average rating for importance for the complete sample and subgroups.

Criterion no.	Grouping by		Area of profession		Scale				Region I			Region II		Segment of profession				Certification expertise	
	Criterion name	Complete sample	Biomass production	Other areas of expertise	Local	National	Supranational	Global	Europe	North America	All other regions	Industrialized countries	Non-industrialized countries	Government	Academia	Industry/ consulting	NGO/ others	Certification expertise	No certification expertise
	N	36–45	27–31	13–14	6–10	23–30	8–9	5–6	19–23	15–21	14–17	37–47	11–14	14–18	15–18	10–12	7–8	9–10	27–32
1	Compliance with laws	X	X	X		X	X		X		X	X		X	X	X	X	X	X
2	Food security	X	X	X	X	X	X		X						X	X	X	X	
3	Land availability							X											
4	Participation	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	
7	Human rights															X			
8	Working conditions			X												X			
11	Property rights and rights of use							X			X		X				X		X
12	Planning				X			X			X		X						
13	Monitoring	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	
17	Microeconomics	X		X		X		X	X	X	X	X	X	X	X	X		X	X
19	Economic stability			X	X									X					X
20	Adaptation capacity				X	X				X		X	X		X				X
21	Energy balance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
22	Nat. res. efficiency	X	X	X	X	X	X		X	X		X		X	X		X	X	X
23	Species protection						X		X								X		
24	Ecosystems protection	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X
25	Ecosystems connectivity																X		
26	Crop diversity		X		X					X				X			X		
30	Soil protection	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
31	Land use change							X			X		X						
32	Water management	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X
33	Waste management	X	X				X		X	X	X	X	X		X			X	
34	GHG balance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
35	Hazardous emissions																		X

Only criteria occurring in one of the groups in the top third are listed. Numbers of respondents vary within each group as respondents rating with ‘No opinion’ were not included. For complete criteria names and descriptions see Appendix 1.

Interestingly, 'certification experts' ranked the identical set of criteria in the top third as the complete sample suggesting that this group may be well qualified to represent bioenergy experts in general.

While the academic and industry/consulting groups ranked the same criteria in the top third, the NGOs and others shared only seven criteria of their top third with those of academia, suggesting that there are some distinct differences of opinion about criteria between these groups. Similarly, experts with global experience shared only seven top third criteria with experts grouped as local. These differences indicate that people's background, values, and spatial scale had an impact on the expert's opinion of sustainability. This emphasizes that a single set of criteria may not be applicable to all bioenergy systems; that accurate assessments of sustainability may require the use of approaches that are flexible enough to account for these differences; and the need for representation from the full range of stakeholders in assessment groups.

Respondents from industrialized countries differed from non-industrialized countries in their top third most important criteria only in their choice of social criteria. Industrialized countries included *compliance with laws* (no. 1) and *monitoring* (no. 13) in their top third, while non-industrialized countries included *property rights and rights of use* (no. 11) as well as *planning* (no. 12).

3.2.2.3. Relations between attributes and rating of the top third important criteria in other attributes. Ratings for relevance were strongly correlated with importance, and practicality ratings were strongly correlated with reliability (Fig. 3). Highly relevant criteria were in general also perceived as highly important, and very practical criteria were also perceived as very reliable.

Seven of the top 12 criteria in importance, namely participation (no. 4), water management (no. 32), natural resource efficiency (no. 22), compliance with laws (no. 1), ecosystem protection (no. 24), monitoring of criteria performance (no. 13), and food security (no. 2) were not ranked in the top third for either practicality or reliability (Table 3). While these criteria are perceived as important, respondents were not confident that they could be measured with the suite of tools currently available. This notion seems to be especially true for the criterion food security (no. 2), which was the only criterion rated in the top third for importance but at the same time rated in the bottom third in practicality (see Table 3). At this point in time the impact of bioenergy on food security is seen as an important issue, but since there are a number of complex factors influencing food security, the connections between the two issues are not clear (e.g. The Guardian [29] vs. Mathews [30]). The low reliability and practicality rankings of these seven criteria in the face of their high importance rankings suggests that there is high uncertainty and/or challenges on how to measure them.

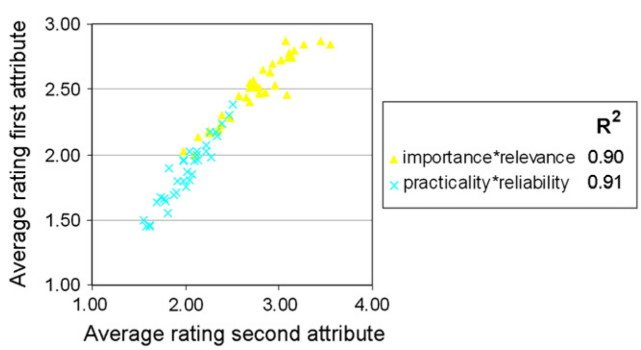

Fig. 3. Correlation of ratings from the complete sample for different attributes for the 35 criteria. The x-axis represents the mean average ratings of the first attribute for a given criteria, while the y-axis represents the mean average rating of the second attribute for the same criteria.

While these findings illustrate a level of agreement on which criteria to include, it is clear that efforts to improve measures and further discussions to come to consensus on the ultimate value of these criteria would be helpful. Stakeholder consultations such as in the FSC process for standard development to certify sustainable forest management can greatly help in attaining such goals [31].

The criteria *compliance with laws* (no. 1) and *food security* (no. 2) were also ranked in the top third in importance but were not in the top third in terms of relevance (Table 3). This may be an indication that these are issues are seen as important but are difficult to link directly to bioenergy systems. Another interpretation for this observation is the dominance of respondents from developed countries where compliance with laws and food security are commonly perceived as problems in less developed countries – neither criteria was rated in the top third of group of experts working in developing countries.

3.2.3. Overall average ratings and consensus within attributes

Respondents tended to rate relevance and importance higher than practicality and reliability (Fig. 3). Importance[4] had the highest mean average rating (2.8) across all criteria (Table 1) followed by relevance (2.5), practicality (2.0), and reliability (1.9).

Fig. 4 shows all criteria sorted according to their level of consensus on importance. Greater agreement on level of importance indicates greater consensus (higher standard deviation). All criteria rated in the top third for importance also had the highest consensus except for *waste management* (no. 33). The same pattern was true for the bottom third of the criteria with *ecosystem connectivity* (no. 25) being an exception as it was ranked in the low third in importance but had only moderate consensus. These observations carry an important implication: that low ranking criteria might be rated low because they are heavily disputed. We also see that social criteria tended to be more controversially rated than environmental ones.

At the attribute level, respondents were more likely to agree on a specific criterion's relevance, practicality, and reliability, with least agreement on its importance. Analysis of consensus by groups showed that experts working on a global scale, from developing countries, and with certification experience showed the highest levels of consensus. Experts working on the supranational and local level, as well as experts with a background in academia, biomass production, and from industrialized countries had somewhat lower consensus ratings than the complete sample.

Only nine criteria[5] showed significant rating differences among groups (see Table 4). One general finding was that the experts with a government/policy background more often rated criteria significantly higher in importance than the other groups. Of the nine, five of them were environmental criteria and differences for these were found among groups by scale, region, and profession. Differences in social criteria – *participation* (no. 4) and *visual impact* (no. 14) – were only significant between regions, suggesting potential cultural influences on these patterns. The economic criteria – *employment generation* (no. 16), *microeconomic sustainability* (no. 17) – were rated significantly lower by biomass production experts than by others.

[4] To make numbers comparable, criteria ratings as 'critical' were counted as 'high' as 'critical' does not exist for other attributes than importance.

[5] Namely participation (no. 4), visual impacts (no. 14), employment generation (no. 16), microeconomic sustainability (no. 17), use of genetically modified organisms (no. 28), use of chemicals, pest control, and fertilizer (no. 29), soil protection (no. 30), water management (no. 32), and potentially hazardous atmospheric emissions other than greenhouse gases (no. 35).

Table 3
The position and rank of criteria in the top third for importance compared to other attributes.

Criterion no.	Nature of criterion	Name	Relevance rank	Practicality rank	Reliability rank
34	Environmental	GHG balance	1 (4)	1 (5)	1 (5)
21	Environmental	Energy balance	1 (1)	1 (1)	1 (1)
30	Environmental	Soil protection	1 (3)	1 (9)	1 (7)
4	Social	Participation	1 (5)	2 (21)	2 (16)
32	Environmental	Water management	1 (7)	2 (13)	2 (12)
22	Environmental	Natural resource efficiency	1 (6)	2 (18)	2 (19)
17	Economic	Microeconomic sustainability	1 (8)	1 (2)	1 (2)
1	Social	Compliance with laws	2 (22)	1 (11)	2 (14)
24	Environmental	Ecosystems protection	1 (2)	2 (20)	2 (11)
13	Social	Monitoring of criteria performance	1 (9)	2 (12)	2 (15)
2	Social	Food security	2 (15)	3 (23)	2 (22)
33	Environmental	Waste management	1 (10)	1 (3)	1 (3)

Criteria are listed according to their importance rating. Numbers indicate position of the respective criterion in the top third (1), second third (2), and low third (3) based on the average rating for each attribute. Numbers in brackets indicate the exact position of the respective criterion. Results are based on feedback from all respondents.

Analyzing by segment of profession revealed more significant rating differences amongst respondents than area of expertise, scale of operation, or region. For instance, *potentially hazardous atmospheric emissions other than greenhouse gases* (no. 35) was rated significantly higher in importance by government/policy professionals than by professionals from NGO/others which in turn ranked it significantly higher in importance than academia.

Comparing the top third most important criteria with results on significant differences in rating between groups, revealed few differences: only *participation* (no. 4), *microeconomic sustainability* (no. 17), *soil protection* (no. 30), and *water management* (no. 32) showed significant rating differences among groups. To advance overall acceptance of a sustainability assessment scheme for bioenergy systems, it might be advisable to clarify definitions or focus research efforts on these four criteria which are commonly perceived as important but are controversial. Their current status with such lack of agreement divides experts and could hamper overall progress in developing assessment frameworks.

Another interesting insight was that respondents associated with industrialized nations ranked the *use of genetically modified organisms* (no. 25) as significantly more important than respondents working in non-industrialized countries. There were no other differences between respondents from industrialized and non-industrialized nations.

3.3. Preference of frameworks

The classic social-economic-environmental (SEE) framework for sustainability was preferred followed by the one developed by Cramer et al. [16] (Fig. 5). Over a quarter of the respondents had no preference for a particular framework. The questionnaire organized the criteria for presentation using the SEE framework, which might have influenced the framework preference choice of some respondents. However, while the SEE framework was selected by half the respondents, the other half made different choices. The Cramer et al. [16] framework is the most holistic to date that has been developed specifically for biomass trade. It formulates sustainability criteria for the production and conversion of biomass for energy, fuels and chemistry.

Group analysis revealed that respondents from the government/policy group were mainly in favor of the SEE framework and significantly differed ($p = 0.05$) from all other professional groups with this ranking. Strong support for the Cramer (2006) framework came from respondents with a background in non-profit

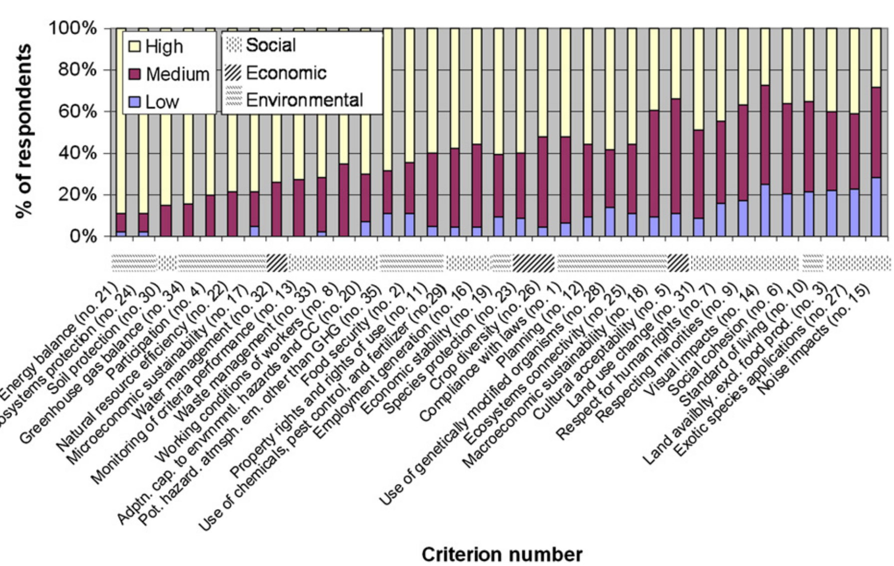

Fig. 4. Respondents' consensus on criteria for the attribute importance. Criteria are sorted along a gradient from high consensus ratings and therefore from a high consensus (left) towards low consensus ratings and a low consensus amongst respondents (right).

Table 4
Significant differences in importance rating criteria by respondents' professional background.

Criterion no.	Criterion name	Area of expertise	Scale of operation	Region of expertise I	Region of expertise II	Segment of profession
4	Participation			North America / All other regions vv vv Europe		
14	Visual impacts			North America vv vv Europe / All other regions		
16	Employment generation	Other Areas of Expertise v Biomass Prod.				
17	Microeconomic sustainability	Other Areas of Expertise v Biomass Prod.				
28	Use of genetically modified organisms				Industrialized c. vv Non-Industrialized c.	
29	Use of chemicals, pest control, and fertilizer			Europe? North America vv All other regions		
30	Soil protection					NGO/ Others? Government/Policy vv vv Academia / Industry/ Consulting
32	Water management		Global? Supra-national? National v Local			Government/Policy vv vv vv NGO/ Others / Academia / Industry/ Consulting
35	Potentially hazardous atmospheric emissions other than greenhouse gases					Industry/ Consulting? Government/Policy v NGO/Others v v Academia

Groups with significant differences printed in black, indifferent groups printed in gray. Groups on top have a higher rating for a given criterion than lower level groups. The symbols and symbolize a significant rating difference between groups on an alpha level of 0.1 and 0.05, respectively, using the Fisher's Exact Test (chapter 2.4). For content of aggregated groups ('All other regions', 'NGO/others') see chapter 3.1. For *N* of groups, see e.g. Table 2.

organizations. Opinions of the academia, industry, and consulting groups were split between the Cramer and the SEE framework. Support for the other frameworks suggested was negligible.

3.4. Limitations

This study is to our knowledge the first attempt to identify and quantify the perceptions of experts about the importance, relevance, practicality, and reliability of sustainability criteria for bioenergy systems. This study identifies some of the areas of agreement and disagreement in the current discussion and points out a number of issues that need to be resolved in order to develop an effective and agreed upon set of criteria that can be used effectively and efficiently. While we recognize the limitations of this study due to the small total sample size, every respondent is an influential bioenergy expert involved in the current debate. Using statistical tests specific to small groups (e.g., Fisher Exact Test) allowed us to more fully analyze for significant differences.

The majority of respondents in our study worked in industrialized regions, namely the EU and North America, specialized in biomass production, and were in academia or government. The addition of practitioners and experts working in non-industrialized

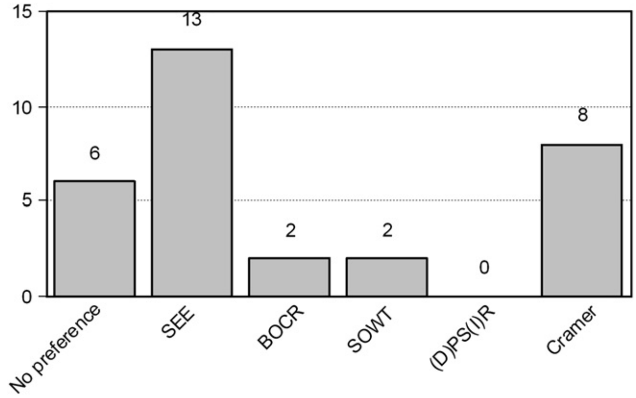

Fig. 5. Number of survey respondents preferring a given sustainability assessment framework for bioenergy systems, population $N = 36$.

countries would improve future studies on criteria preferences. However, our experience suggests that this uneven distribution corresponds with representation of bioenergy experts in many current bioenergy sustainability discussion panels. While this study reasonably represents the current discussion, it once again emphasizes the need for intensified efforts to include those bioenergy experts which might be underrepresented especially in the light of the differences in ratings that we found.

4. Summary

This study provides baseline data on how bioenergy experts rate sustainability criteria that are currently under discussion for bioenergy systems in terms of importance, relevance, practicality, and reliability attributes. This study identifies areas of agreement and disagreement among the experts including the following key items:

- *Energy balance* and *greenhouse gas balance* received the highest ratings on all four attributes.
- *Soil protection* and *greenhouse gas balance* were contained in the top third for across all subgroups of experts.
- Each criterion was ranked as 'critical' at least once, only *greenhouse gas balance* and *energy balance* were ranked as critical by more than half of respondents.
- The top third criteria for the importance attribute were compliance with laws, food security, participation, monitoring of criteria performance, microeconomic sustainability, energy balance, natural resource efficiency, ecosystems protection, soil protection, water management, waste management, and greenhouse gas balance.
- The ten criteria that rated lowest in importance were heavily disputed, i.e. some respondents rated them very high while many scored them as low.
- There was s tendency for greater disagreement in the rating of the importance of social criteria compared to environmental ones.
- Although *participation*, *microeconomic sustainability*, *soil protection*, and *water management* ranked high in importance, individual subgroups of experts had significantly different opinions about them.
- Environmental criteria were rated as more important and relevant while economic criteria were perceived as more reliable and practical.
- Social criteria and especially criteria of local significance such as *visual impact*, *standard of living*, or *social cohesion* – though perceived as relevant – ranked lowest in reliability, practicality, and importance.
- Environmental criteria showed highest consensus amongst experts, while social criteria showed least consensus.

The following statements summarize findings of differences across subgroups of experts:

- Certification experts chose an identical set of the top 12 most important criteria as the complete sample, suggesting they are a good representation of all experts.
- At least eight criteria of the complete sample's most important twelve (or top third) criteria were also represented in each of the expert subgroups.
- Experts working on a global scale, from developing countries, and with certification experience showed the highest consensus amongst groups.
- Experts working on a local level or in academia showed low consensus within their respective groups.
- Only social criteria were rated significantly differently between regions. Industrialized and non-industrialized countries differed only in their top third important social criteria.
- Experts from different professions were most likely to rate criteria differently. Experts from industry and consulting agreed to a large extent with academia, but experts from NGOs and government rated criteria differently than other groups.

5. Conclusions

We conclude that the majority of criteria currently under discussion are valid for serious consideration due to the high level of respondent importance ratings and no criteria should be eliminated at this point. It is also clear that continued dialogue is needed to achieve consensus about which criteria are most important, relevant, practical and reliable. Furthermore, that the lowest consensus exists between different professions rather than region, scale of operation, or primary area of expertise suggests a need to strengthen interdisciplinary exchange among experts. In order to gain expert consensus on key criteria (top third, critical ones, etc.) more exchange is needed between disciplines and scales, even when expert input can only be received from a few regions. Similarly, we find that the ten criteria that rated lowest in importance had much less consensus on their value than criteria rating higher, indicating a need for further deliberation.

The general survey approach proved to be valuable to measure the current level of consensus and uncertainty in the debate on bioenergy sustainability approaches. Periodic efforts to gather input of and exchange among experts and other stakeholders with a wide range in professional backgrounds would be extremely valuable. Special effort should be made to include experts with a local focus *and* working outside of Europe and North America.

To move the discussion on sustainability of bioenergy systems forward, further discussion and research on how to measure criteria that are identified as important will be essential (see also van Dam et al. [9]). The research should focus on criteria ranking high in importance but low in reliability and practicality, namely *food security* (no. 2), *participation* (no. 4), *water management* (no. 32), *natural resource efficiency* (no. 22), *compliance with laws* (no. 1), *ecosystem protection* (no. 24), and *monitoring of criteria performance* (no. 13).

The significant rating differences amongst experts prompt us to conclude that a single fixed set of criteria might not be advisable for bioenergy systems. There are enough differences that this approach is likely to create friction and disagreement. This suggests sustainability assessments will be more successful if they are flexible for different spatial and temporal scales and can be applied to each project independently. Criteria included or the weighting of the criteria might need to change from case to case in order to achieve a wider base or support for sustainability assessments. There may be a set of agreed upon criteria that should be included in all assessments, for instance the top third most important criteria as identified in this study, while others could be selected by stakeholders associated with each assessment. In this case, agreement amongst a large group of experts or stakeholders would only be needed to identify the pool of criteria to select from. Such a process-oriented structure rather than goal oriented approach for certification is already used by the ISO 14001 standard (e.g. Hayward and Vertinski [32]), the ISO BS7750, or the European Union's EcoManagement and Audit Scheme (EMAS) [33], which offer frameworks for certification of environmental management systems but do not specify standards or goals. In such an approach, the certification process itself gets certified rather than the outcome. However, while such approaches can effectively embrace different scales, number of stakeholders involved, project boundaries, and conditions, there is a risk of working to a lowest common denominator when it may be more appropriate to set higher standards.

Respondents expressed concern about the lack of holistic concepts to measure sustainability of bioenergy systems. Participatory quantitative or qualitative modeling exercises have proven useful in creating such an holistic overview on complex issues in fields related to bioenergy and is in the tradition of action research [34] or adaptive management (e.g. Holling [35]). In these approaches, the goal is to detect leverage points, i.e. those parts of a system where a small change can create important changes. Such leverage points coincide with high impact criteria [5]. Multi-criteria analysis appears to be a promising tool to implement such participatory system-based assessments, integrating various stakeholders' voices and values while acknowledging each project's unique characteristics [36]. By compiling criteria sets as it has been done to this point, the first steps towards a systemic view have been taken, but a holistic approach is still missing. In order to develop an approach that is acceptable across a broad range of groups, we must ask the following questions: How can we generalize the obstacles experienced by bioenergy implementations like e.g. lack of local participation [26]? How can we predict the impact of bioenergy implementation on society?

Current sustainability efforts based on the well-known social-economic-ecological three-legged stool framework have advanced the discussion and increased the understanding that many different factors need to be considered. However, efforts to assess sustainability based on the social-economic-ecological concept are still somewhat ad hoc in their approach to identify the criteria used to assess each of the three factors [14]. This concept does not give us the analytical capability to determine whether an influencing factor has been left out or has been over emphasized, thereby limiting our ability to interpret the outcomes of such sustainability assessments. Therefore, this ad hoc approach leaves many questions open in terms of which factors are chosen or left out, who chooses them, how trade-offs are addressed, what feedback loops exist amongst criteria, and how they influence decisions concerning sustainability. It may be in the best interest to expand the conversation to ask if the list of criteria in this study and in the literature was complete and comprehensive enough. To that end the use of a systems approach would provide a more systematic and logical way to deal with this issue. The inclusion of a diversity of interests would also enhance this effort. We hope that our effort can assist the ongoing international debate and search for sustainability assessment criteria and frameworks for bioenergy systems in general and the large and complex system of international biofuels trade frameworks in particular.

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Appendix 1

Sustainability criteria used in the survey with explanations and categories. Sources included Cramer et al. [16], van Dam et al. [17], Fritsche et al. [18], Jürgens and Best [19], Lewandowski and Faaji [20], Modi et al. [21], Reijnders [22], Five Winds International [23], Smeets et al. [24], the Sustainable Bioenergy Wiki [25] of the Roundtable on Sustainable Biofuels (RSB) Lausanne, Upreti [26], and the World Energy Council [27]. Depending on the source, criteria descriptions were streamlined in an effort to represent the same meaning across several sources and might therefore diverge from original wording.

Criterion no.	Criterion name	Nature of criterion	Criterion explanation	Sources
1	Compliance with laws	Social criterion	Complying with all applicable laws and internal regulations like certification principles, countering bribery	[19,20,25]
2	Food security	Social criterion	Enough land locally available for food production including agricultural set aside land, preference of marginal sites for energy crops	[16–21,24,25]
3	Land availability for other human activities than food production	Social criterion	Enough land locally available for housing, energy (e.g. firewood), recreation, and other resource supply	[25]
4	Participation	Social criterion	Inclusion of stakeholders in decision making; facilitation of self determination of stakeholders	[16,19–21,25,26]
5	Cultural acceptability	Social criterion	Consideration of spiritual values, handling of local knowledge	[16,19,23,25,26]
6	Social cohesion	Social criterion	Migration and resettlement, wealth distribution, fair wages, intergenerational equity, charity	[16–20,23–26]
7	Respect for human rights	Social criterion	Health services, liberty rights, security, education	[16–21,24,25]

(*Appendix 1 continued*)

Criterion no.	Criterion name	Nature of criterion	Criterion explanation	Sources
8	Working conditions of workers	Social criterion	Worker health, work hours, safety, liability regulations, exclusion of child labor	[16–20,23–25]
9	Respecting minorities	Social criterion	Recognition of indigenous peoples' rights, gender issues	[16,19,20,25]
10	Standard of living	Social criterion	Public service support, access to energy services (e.g. electricity lifeline tariffs)	[16,19,20,23,25,26]
11	Property rights and rights of use	Social criterion	Land and resource tenure, dependencies on foreign sources (e.g. financial investments, knowledge) fair and equal division of proceeds, customary rights	[16,18,20,25]
12	Planning	Social criterion	Stating clear objectives, a management plan is written, implemented, and updated as necessary	[20,25]
13	Monitoring of criteria performance	Social criterion	Monitoring systems in place for all criteria (e.g. leakage or additionality in GHG accounting)	[20,25]
14	Visual impacts	Social criterion	Visual effects of construction and feedstocks on landscape	[26]
15	Noise impacts	Social criterion	Noise from production, transportation and conversion processes	[25,26]
16	Employment generation	Economic criterion	Number jobs created, quality of jobs created	[19,20,23–27]
17	Microeconomic sustainability	Economic criterion	Cost-efficiency incl. startup costs, internal rate of return, net present value, payback period	[16,19,20,23,25,27]
18	Macroeconomic sustainability	Economic criterion	Trade balances, foreign investments, financial flows across project boundary, changes in overall productivity, 'economic development'	[17,19,20,25]
19	Economic stability	Economic criterion	Project lifetime, degree to which applied technology and operational aspects are proven, flexibility to changes in demand and supply, product diversification	[16,20,23,25]
20	Adaptation capacity to environmental hazards and climate change	Environmental criterion	Diversification of feedstocks, available knowledge on site demand of feedstocks	[20,25]
21	Energy balance	Environmental criterion	Conversion efficiencies, energy return on investment, energy return per hectare	[20,25]
22	Natural resource efficiency	Environmental criterion	Efficient use of resources at all stages of the system	[19,20,23,25,27]
23	Species protection	Environmental criterion	Protection of rare, threatened, or endangered species	[17–20,24–26]
24	Ecosystems protection	Environmental criterion	Safeguarding protected, threatened, representative, or other valuable ecosystems (e.g. forests), protecting internal energy fluxes/metabolism	[16–20,23–25]
25	Ecosystems connectivity	Environmental criterion	Preventing land fragmentation, e.g. presence of wildlife corridors, etc.	[16–20,23–25]
26	Crop diversity	Environmental criterion	E.g. impacts and risks associated with monocultures like its impacts on landscape and wildlife, and its susceptibility to catastrophic failure	[19,25]
27	Exotic species applications	Environmental criterion	Invasiveness, risks to other species and land uses	[20,23,25]
28	Use of genetically modified organisms	Environmental criterion	Appliance with law, risk to other land uses	[23,25,26]
29	Use of chemicals, pest control, and fertilizer	Environmental criterion	Insecticides, herbicides, chemicals in the conversion process, impacts on surrounding environment	[16,19,20,24,25]
30	Soil protection	Environmental criterion	Impacts on soil fertility like. changes in nutrient cycling, rooting depth, organic matter, water holding capacity, erosion	[16–22,25]
31	Land use change	Environmental criterion	Impacts of land conversion on energy fluxes, radiation balance, roughness of land cover, biochemical fluxes, hydrological cycles which eventually affect ecological balances	[18,20–23,25,26]
32	Water management	Environmental criterion	Surface and groundwater impacts, riparian buffers, irrigation and cooling cycles and waste water management	[16–25]
33	Waste management	Environmental criterion	Disposal of ashes, sewage, hazardous/contaminated solid and liquid material	[16,19,20,23,26]
34	Greenhouse gas balance	Environmental criterion	GHG balance of system covering CO_2, CH_4, O_3, NO_2, H_2O	[17–23,25]
35	Potentially hazardous atmospheric emissions other than greenhouse gases	Environmental criterion	Emissions of SO_x, CO, NO_x, and particulates	[16,17,20,23,25,26]

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