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Towards integrated sustainability assessment for energetic use of biomass: A state of the art evaluation of assessment tools

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ABSTRACT

Biomass is expected to play an increasingly significant role in the 'greening' of energy supply. Nevertheless, concerns are rising about the sustainability of large-scale energy crop production. Impacts must be assessed carefully before deciding whether and how this industry should be developed, and what technologies, policies and investment strategies should be pursued. There is need for a comprehensive and reliable sustainability assessment tool to evaluate the environmental, social and economic performance of biomass energy production. This paper paves the way for such a tool by analysing and comparing the performance and applicability of a selection of existing tools that are potentially useful for sustainability assessment of bioenergy systems. The selected tools are: Criteria And Indicators (C&I), Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), Cost Benefit Analysis (CBA), Exergy Analysis (EA) and System Perturbation Analysis (SPA). To evaluate the tools, a framework was constructed that consists of four evaluation levels: sustainability issues, tool attributes, model structure, area of application. The tools were then evaluated using literature data and with the help of a Delphi panel of experts. Finally, a statistical analysis was performed on the resulting data matrix to detect significant differences between tools. It becomes clear that none of the selected tools is able to perform a comprehensive sustainability assessment of bioenergy systems. Every tool has its particular advantages and disadvantages, which means that trade-offs are inevitable and a balance must be found between scientific accuracy and pragmatic decision making. A good definition of the assessment objective is therefore crucial. It seems an interesting option to create a toolbox that combines procedural parts of C&I and EIA, supplemented with calculation algorithms of LCA and CBA for respectively environmental and economic sustainability indicators. Nevertheless, this would require a more comprehensive interdisciplinary approach to align the different tool characteristics and focuses.

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1. Introduction

1.1. Current state of sustainability assessment

The concept of sustainability has evolved considerably since it was mentioned for the first time in the forestry sector of the 18th century [1–8]. Nowadays, the standard definition of sustainable development provided by the Brundtland Commission "to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [9] is generally recognised as a standard and a starting point for most who set out to define the concept. The concept is often depicted schematically using three overlapping circles for the target dimensions of environment, economy and society, to which might be added an institutional dimension [10]. More detailed discussions of different concepts of sustainability can be found in various publications [11–13].

For the transition towards a more sustainable society, comprehensive but efficient and reliable assessment tools are needed. Devuyst et al. [14] define sustainability assessment as "a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable." Following Ness et al. [15] the purpose of sustainability assessment is to provide decision-makers with an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society more sustainable. Based on the four dimensions of sustainability, several comprehensive frameworks for integrated assessment have been developed [16–18]. In 1996, a group of researchers have established a set of practical guidelines in the form of overarching principles that provide a link between theory and practice for the whole assessment process from system design and identification of indicators, through field measurements and compilation to interpretation and communication of results, which are known as the "Bellagio Principles" [19]. In the last decade, a number of concepts have been developed that aim at upgrading the operationalisation of the vision of sustainability. This resulted in a diverse field of approaches that claim that they can be used for assessing sustainability in many different sectors [15,18–27]. Sustainability assessment has increasingly become associated with the family of impact assessment tools such as Life Cycle Assessment, Ecological Footprint, Environmental Impact Assessment and Strategic Environmental Impact Assessment [8,28].

1.2. Problem statement, aim and approach

In this research, the assessment focus is on the bioenergy sector. Worldwide, the potential of biomass to contribute to reductions in greenhouse gas (GHG) emissions, to improved energy security and to rural diversification and development is recognised [16]. Several bioenergy policies such as the Brazilian Biofuel Law, the Indian Biofuel Policy, the U.S. Renewable Fuel Standard, and European policies such as the Renewable Energy Directive, Strategy on Biofuels and the Biomass Action Plans push the implementation of energy derived from biomass in order to reduce fossil fuel dependency or to meet greenhouse gas reduction targets. These policies are a source of increasing concern due to questions over the sustainability of large-scale bioenergy crop production. Potential negative impacts include direct and indirect land use change [29–32] and biodiversity loss [33,34], availability of water resources [35–38], rising agricultural commodity prices and threats to food security [39–44]. These risks have to be weighed against potential benefits such as improved greenhouse gas balance, employment and income generation, rural development, conversion of conventional industries and increased security of energy supply [45–47]. Therefore, the environmental, social and economic impacts of bioenergy development needs to be assessed carefully before deciding whether and how this industry should be developed, and what technologies, policies and investment strategies should be pursued. In this context, some governments and institutions started developing sustainability tools and standards to evaluate the environmental, social and economic performance of biomass energy production. At the same time, companies are willing to integrate more sustainable strategies in their energy management and are looking for practical and reliable sustainability assessment tools to assess different energy system possibilities. However, the high variability in biomass sources, conversion technologies and contexts complicate such assessments. A variety of assessment tools for sustainability evaluation of production systems has been developed in the past, each showing a different procedure and field of application [48].

The general aim of this paper is to contribute to the development of a comprehensive, yet practical and reliable tool for sustainability assessment of bioenergy systems. Since many tools currently exist, there is more of a need to highlight complementarities or possibilities for integration rather than to generate new tools. Therefore, the specific goal of this paper was to make a comparative evaluation of a selection of existing tools to which degree these tools are able to incorporate the different dimensions of sustainability of bioenergy systems. The research approach is presented in Fig. 1. First, an evaluation framework is constructed in which the tools are evaluated. In a next step, the evaluation of the selected tools is made. The resulting data matrix is then statistically analysed to detect significant differences between tools and as a conclusion, strengths and weaknesses of the tools are highlighted and possibilities for their integration in a more comprehensive tool are made.

2. Materials and methods

2.1. Selection of existing assessment methods

A wide range of sustainability assessment methods has been developed in recent years hence some initial selection was needed. Our selection strategy was twofold. On the one hand we chose some well-known and commonly used but conceptually very different

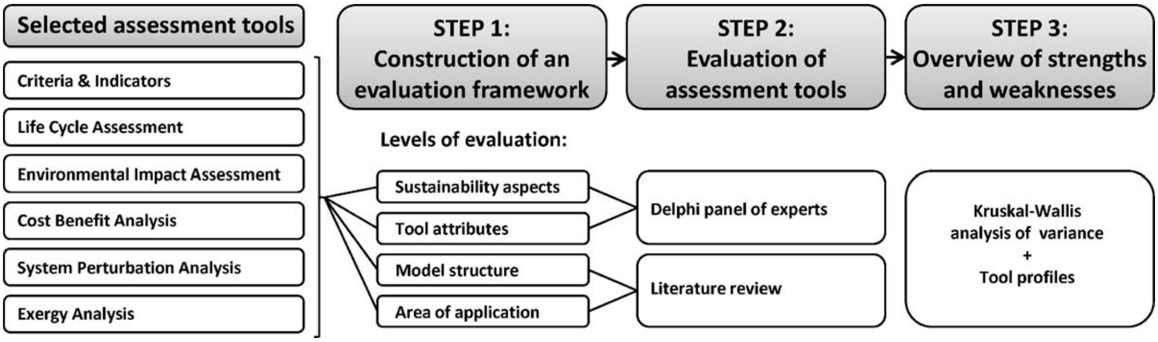

Fig. 1. Flow chart of the tool evaluation process.

tools for sustainability assessment: Criteria And Indicators (C&I), Life Cycle Analysis (LCA), Environmental Impact Assessment (EIA) and Cost Benefit Analysis (CBA). On the other hand we added two rather uncommon but conceptually promising tools. Exergy Analysis (EA) is a method in thermodynamics able to account material and energy flows all in the same unit. System Perturbation Analysis (SPA) is a tool that performs an accountancy evaluation after perturbation of a system (e.g. increase in bioenergy production) and compensation of the disturbances. SPA was specifically designed for the Belgian system. The result of the selection is a mixture of tools with varying scopes and assessment strategies, focussing on different systems (products, services, projects and/or economies) and various impacts. A short introduction to each tool is given in Box 1

Box 1

Criteria and Indicators (C&I) can be used for a wide range of applications such as eco-certification at the management unit level [49], policy evaluation at the regional or national level [50,51], or as a generic assessment tool for specific environmental, social, economic or institutional sustainability issues. The use of C&I is a common way to describe and monitor complex systems, and to provide information to decision makers and the public. Some well-known sustainability criteria initiatives in the field of bioenergy [52–54] are the criteria of the Cramer Commission [17,55], the Renewable Transport Fuels Obligation [56–58], the European Renewable Energy Directive [59], the Round Table for Sustainable Palm Oil [60,61], the Round Table on Responsible Soy [62], the Basel Criteria for Responsible Soy Production [63], the Roundtable on Sustainable Biofuels [64–66], the Forest Stewardship Council FSC [67] and the Programme for the Endorsement of Forest Certification PEFC [68,69].

A well-established method is *Life Cycle Assessment* (LCA). LCA has been used in varying forms over the past 35 years to evaluate the environmental impacts of a product or a service throughout its life cycle. It is an approach that analyses real and potential pressure that a product has on the environment during its whole life cycle from cradle to grave, including raw material acquisition, production process, use, and disposal of the product [70]. The International Standards Organisation (ISO) has established guidelines and principles for LCA that have been further interpreted and developed by many authors [25,71–76]. LCA results provide information for decisions regarding product development and ecodesign, production system improvements, and product choice at the consumer level. Numerous Life-cycle Assessments have been performed in the bioenergy field [77–88], as well as for a multitude of other product and service areas.

Environmental Impact Assessment (EIA) has been used since 1960s for evaluating potential environmental impacts – considering natural, social and economic issues – that a proposed project may have, with the aim to reduce its negative effects [89]. The purpose of the assessment is to decide whether to proceed with the project and to identify impact mitigating measures. The International Association for Impact Assessment (IAIA) defines an Environmental Impact Assessment as the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made [90]. In the EU, a directive that made EIA compulsory for proposed public and private projects (e.g. construction projects) that are likely to have environmental impacts was introduced in 1985 [91,92]. EIA has also been introduced in the legislation in many other countries [93]. Due to such legal requirements, there are strict guidelines for the EIA process in the EU and other countries [89]. In literature, no EIA studies were found for bioenergy projects in particular.

Cost Benefit Analysis (CBA) is an applied welfare economics tool with roots reaching back to the early 20th century. It is used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits. In the realm of sustainability assessment, CBA can be an effective tool for weighing the social costs and benefits of different alternatives in connection with e.g. energy and transports [94]. It is this aspect of measuring expected benefits, or placing monetary units on the benefits, e.g. biodiversity, that is often a challenge within CBA [95]. A number of CBA studies were found regarding bioenergy projects [96–100].

Exergy Analysis (EA) is a powerful thermodynamic accounting technique for assessing and improving the efficiency of processes, devices and systems, as well as for enhancing environmental and economic performance. As a multidisciplinary concept, exergy applications are observed in various fields, including mechanical and chemical engineering as well as economics, management, physics and biology. Consequently, EA is used increasingly by industries and governments throughout the world, particularly with the aim of improving energy sustainability. In depth explanations of the concept and application of exergy analyses are delivered by many scientist [101–109], and examples of exergy assessment related to the bioenergy field can be found in [110–112,102,113,114].

A new method called *System Perturbation Analysis* (SPA) was recently developed by the Free University of Brussels (VUB) [115]. SPA differs from a conventional Life Cycle Analysis (LCA) mainly because it looks to alternations in resource balances (so-called perturbations) within a specific geographical system and the resulting effects, rather than comparing life-cycle trajectories. Therefore SPA is able to identify the best usage of limited resources such as hectares, wood waste or imports, in terms of fossil energy savings or GHG emissions within a given system. Comparative results of such a System Perturbation Analysis for the use of wood for transport, heat and power applications are presented in the study of Bram et al. [115] and results for biomass in a natural gas combined cycle power plant can be found in the study of Delattin et al. [116].

2.2. Step 1: construction of an evaluation framework for sustainability assessment tools

The selected tools represent different ways of looking at a given assessment challenge and they convey different information to the decision process. Each tool collects, structures and evaluates information about specific issues and presents it in a specific way. Which specific tool will be used in a specific situation depends on the general conceptual view of the decision maker, the context for which to take a decision and the specific objectives of the assessment [117]. In order to make a clear evaluation of the selected tools and to compare their characteristics in terms of objectives, focus and approach, an evaluation framework is constructed. The definition of an evaluation framework depends on the specific aim of a study, which in our case is the development of a comprehensive yet practical and reliable method for sustainability assessment of bioenergy systems. 'Comprehensive' means that as many environmental, social, economic and institutional sustainability issues as possible should be considered in the tool. A 'practical' tool makes demands on the effective use of the tool and is related to the amount of data that are needed, which procedure is applied, how the results are reproduced, and in which context the tool can be used. 'Reliable' requires a transparent and science based model structure that takes all inputs, outputs, interactions and interdependencies at each stage of the bioenergy system into account [118]. All these requirements which determine whether a tool is suitable or not are addressed in the evaluation framework, using four levels of comparison: (i) sustainability issues; (ii) tool attributes; (iii) model structure; and (iv) area of application. The first two levels could be analysed numerically by a Delphi panel of experts, whereas the last two levels, which are descriptive, are evaluated based on literature review. These four levels of comparison of the evaluation framework are further elaborated in the following paragraphs.

2.2.1. Issues of sustainability

An important part in determining the ability of a tool to serve as a sustainability assessment tool for bioenergy systems is to check which sustainability issues are addressed by the tool. For this aim, a comprehensive list of relevant sustainability issues was constructed, based on sustainability requirements for bioenergy systems mentioned in literature, e.g. [2,17,52,56,57,59,62,63,119–122]. The resulting list, organised along the four dimensions of sustainability, is shown in Table 1. It was chosen not to go in too much detail to keep the list operational. A few indicators are added as an example.

2.2.2. Tool attributes

Assessment tools ideally have a number of characteristics which facilitate their application with respect to the use of data, the followed methodological procedure, the reproduction of the results, and finally, the use of the tool in general. In this second level of the evaluation framework, it is tried to consider a large range of facilitating attributes that a sustainability assessment tool for bioenergy systems might have. A list of attributes was made using information about tool attributes, found in various literature resources [1,48,122], complemented with own expertise. The result can be found in Table 2, in which attributes are given with respect to data used in the tool, tool procedure, tool results, and use of the tool.

2.2.3. Overall model structure

Literature review of assessment frameworks, tools and comparison studies has demonstrated that tools can be categorised based on several features with regard to the overall model structure e.g. [11,15,77,95,123–126]. Of all the features encountered in literature, those that seemed relevant for sustainability assessment of bioenergy systems were withheld for the third level of the evaluation framework of this study. After a short explanation of a few general tool aspects such as tool description, tool concept, object of analysis, type of comparison, degree of standardisation or harmonisation, and frequency of use, some more specific methodological aspects are addressed: time frame, spatial scale, concept focus, quantitative or qualitative character, reproduction of results, assignment of weight scores, and sensitivity and uncertainty analysis. A short description of the different aspects follows.

Table 1
Set of sustainability issues for bioenergy systems (examples of indicators between brackets).

Sustainability issues and some of their indicators
Environmental dimension
Air quality (emissions of GHG, nitrogen, POP's)
Soil quality (nutrient balances, accumulation of heavy metals, soil compaction and erosion)
Land use (amount of land used, leakage effects)
Water quality (water pollution, eutrophication, pesticide residues)
Use of ground and surface water
Biodiversity and preservation of sensitive ecosystems (use of GMO's/exotic species, preservation of habitats and high conservation value forests, avoidance of pollution of neighbouring ecosystems)
Deforestation
Desertification and drought
Landscape view (landscape variation, conservation of typical elements)
Use of agrochemicals
Waste management (minimization, sorting, disposal, recycling)
Use of energy (energy balance)
Use of fossil resources
Social dimension
Labour conditions (freedom of association, collective bargaining, minimum wages, discrimination)
Protection of human safety and health (protection of human health, safe and healthy work environment)
Protection of human rights (rights of children, women, indigenous people, discrimination)
Access to resources ensuring adequate quality of life (access to potable water, sanitary facilities, adequate housing, education and training, transportation, and health services)
Food and energy supply safety (quantity and quality of food available, energy supply)
Capacity building (building and use of local labour and skills)
Democratic participation (stakeholder involvement)
Protection of property rights and user ownership (land tenure conflicts, equitable land ownership)
Fair trade conditions (transparency and accountability of negotiations, fair and equal remuneration)
Social acceptance (acceptance of the business by producer, consumer and local population)
Economic dimension
Viability of the business (net present value, minimisation of costs, adequate funding)
Long term perspective (long-term commitments, contracts and management plans)
Reliability of resources (security of supply)
Reliability of the used technology (adequately proven technology)
Risk minimisation
Strength and diversification of local economy
Reliability of energy
No blocking of other desirable developments
Institutional dimension
In respect with local, national and international policy and legislation
Institutional capacity
Institutional well-being
Environmental management

The *tool description* describes the purpose of the tool, the reasoning behind the development of the tool. The *tool concept* gives an overview of the methodology followed or the different steps during application of the tool. The *object of analysis* specifies which object is being analysed by the tool, e.g. a product, a function or an economy. Most tools include some *type of comparison*, either between different alternatives, or within a studied system, or against a reference. It differs from tool to tool and is often related to the object analysed in the decision process [123]. Also the *degree of standardis-*

Table 2
List of attributes used to describe the characteristics of the evaluated tools.

Tool attribute	Attribute explanation
Data	
Availability	Data needed to apply the tool are readily available
Need	Balanced amount of data needed to apply the tool
Type	Preference for quantitative (metric) data input
Integration	Ability to combine descriptive and quantitative data
Correctness	Correctness of data used
Procedure	
Flexibility	Model procedure is dynamic, can easily be adapted or complemented
Coverage	Degree to which multiple sustainability issues of the four dimensions are integrated
Objectivity	Model is not susceptible to the subjectivity of the executor
Transparency	Transparency of the evaluation procedure
Validation	Ability to validate evaluation results
Time scale	Ability to process dynamic data
State-of-the-art	Degree to which the tool is operational
Results	
Univocity	Results are consistent, no contradictions in the results
Simplicity	Results are possible to understand by stakeholders, no expert knowledge required
Type	Results are preferably quantitative
Clarity	Results are compact and clear, no long lists or extensive reports
Communication	Results are represented graphically, easy to interpret
Use	
Flexibility	Ability to integrate inputs of the stakeholders
Accessibility	Possibility to interpret results without expert intervention
Application cost	Low cost to execute the evaluation task
Application field	Ability to execute evaluation tasks on different levels (micro, macro, . . .)
Time consumption	Low time demand to execute the evaluation task
Handiness	The model is easy to use
Assistance	Availability of experts to render assistance

ation or harmonisation is an important aspect, even if many aspects are under continuous development [95]. If different users apply the tool in separate ways, evolution will make it harder to keep the tool homogenous in the future and to compare or share data and results. Another aspect is the *frequency of use*, which gives information about how often the tool is used, and sometimes also where it is used. The *time frame* both indicates the time perspective applied to the object analysed which can be retrospective or prospective, as well as the time horizon of the object itself and the related impacts. Approaches mainly used in the context of accounting, tracking and monitoring on-going (e.g. year on year) progress can be called retrospective, while those used to predict future situations can be called prospective [123]. The time horizon indicates whether the tool is a snapshot in time, or whether it considers the whole life time of a product, project or process and/or their impacts. The *spatial scale* is related to the spatial boundaries and horizon of the object analysed. Spatial boundaries can be the boundaries of a country or town, but also boundaries surrounding a section in a product chain, or the boundary between nature and the human system [95]. The spatial horizon may include a single site, many sites, or no sites e.g. in case of product design. The spatial scale can therefore be categorised as site specific focus and non- or multi-site focus [123]. The *concept focus* indicates whether a tool emphasises procedure or focuses on the construction of a defined type of computational algorithm. Procedure aims at describing the best way to reach a decision, whereas algorithms are aimed at finding the better decision [123]. Tools can have a purely *quantitative character* or rather qualitative, or both quantitative and qualitative. Under *reproduction of results*, information is given about how the results are presented, whether they are listed with different units, or aggregated in one single outcome. Another aspect that is regarded, is the possibility within the tool to *assign weight scores* and how this is performed. In a final part of the evaluation, information is gathered on the need to conduct and the integration of a *sensitivity and/or uncertainty* analysis in the tool.

2.2.4. Application of the tools

In the fourth level of the evaluation framework the purpose is to focus on the application of the tools. For that purpose, various aspects can be taken in consideration such as the overall purpose of the tool (communication, decision-support or learning), the user category (companies, government/authorities, NGOs) or the object of analysis (product, function or economy) [123]. A study conducted by Ness et al. [15] performs a categorisation of assessment tools based on the temporal focus of the tool along with the object of focus of the tool. The temporal focus can be either retrospective (indicators/indices), prospective (integrated assessment) or both (product-related assessment). The object of focus of the tools is either spatial, referring to a proposed change in policy (indicator/indices and integrated assessment), or at the product level (product-related assessment). For this paper, the same exercise was performed as well as an evaluation based on the development stage of the tool and the frequency of application.

2.3. Step 2: evaluation of existing assessment tools

In the second step of the study, the newly constructed evaluation framework is used to evaluate the six selected assessment tools.

In the first two evaluation levels (sustainability issues and tool attributes), the research was carried out with the use of a Delphi panel of experts. The Delphi method is a popular technique for forecasting and an aid in decision-making based on the opinions of experts, which has been in existence for over half a century [127]. The aim of the study was to gather a group of scientist with expertise in the sustainability assessment field, including at least one expert for each of the selected assessment tools. Unfortunately, no experts could be included for exergy assessment. As a consequence, the Exergy Analysis tool was only evaluated in the third and fourth level of the evaluation framework, for which no Delphi expertise was required. The experts first received documentation about the aim and planning of the study by e-mail. Next, an interactive meeting was organised, during which grades were assigned to each of the tools for each of the sustainability issues and tool attributes (level 1 and 2 of the evaluation framework). Experts were able to jointly discuss and exchange thoughts during the assignment. The grades were ordinal numbers from one to five by which one stands for the lowest score and five for the highest.

The material used to evaluate the assessment tools in level 3 and 4 of the evaluation framework (overall model structure and tool application) consisted of scientific papers describing the methodology of the tools, literature related to specific application of each of the assessment tools in the field, and practical examples.

2.4. Step 3: overview of strengths and weaknesses

The evaluation of the first and second level of the evaluation framework, carried out by the Delphi panel of experts, resulted in two data matrices consisting of ordinal scores, giving an overview of the strengths and weaknesses of the different tools. In order to detect significant differences between tools, the data matrices were statistically analysed. Because of the ordinal character of the data, a Kruskal–Wallis analysis of variance was performed. The Kruskal–Wallis test is a non-parametric method for testing equality of population medians amongst groups. However, in this study we had only one observation for every evaluator variable separately, so no medians could be generated. Therefore, significant differences ($\alpha = 0.05$) between tools were evaluated at the subgroup level. In the data matrix of the sustainability issues, the subgroups are the environmental, social, economic and institutional dimension. In the data matrix of the tool attributes, the subgroups are data, procedure, results and use.

The data gathered about the overall model structure in the third level of the evaluation framework are reproduced in the form of tool profiles, which enables rapid comparison of the different assessment tools.

3. Results and discussion

In comparing sustainability assessment tools, many different tool characteristics and aspects are involved. Therefore, an evaluation framework was constructed, distinguishing four levels of evaluation: issues of sustainability, tool attributes, overall model structure and tool application, in which tools were evaluated. While recognising the importance of such a comparative study, it is important to note that the results are not always very straightforward because of many reasons. Although the Delphi method is considered as a very valuable way to provide information, it cannot be avoided that expert valuations are prone to some degree of subjectivity. Furthermore, most of the considered tools are flexible, are developing over time, and not always well defined. Available literature might be outdated or not complete. At last, tools can be developed for many different reasons, and therefore do not always serve for a straightforward comparison. It is important to keep these issues in mind while examining the results of this study. In the following paragraphs, results are discussed for each evaluation level.

3.1. Issues of sustainability

As sustainability is a complex and multidimensional subject, integrated sustainability assessment requires a multicriterial approach. For this study, important sustainability issues were listed for the bioenergy field and tools were valuated with the use of a Delphi panel of experts. The lowest score of 1 was given in case the tool did not address the aspect at all; a value of 2 when the aspect was only addressed to a very limited extend; a value of 3 when the tool addresses the aspect with a certain methodology but only partially; a value of 4 in case the aspect is very well addressed, but still could be improved significantly; and a value of 5 in case the aspect involved is fully covered (Table 3).

The results give a clear overview of the sustainability areas that are covered by the different tools. It can be noticed that most of the tools are environmentally focused. Except for a few minor issues, LCA, EIA and SPA only take the environmental dimension into account, whereas CBA is rather an economic tool incorporating some environmental issues. For the environmental dimension, there is a broad agreement in the scientific community that LCA is one of the strongest players in the assessment field [70,83], although C&I and EIA also show good performances. The scope and methodologies of EIA have evolved greatly over the past decade. Advances include consideration of biodiversity and climate change

Table 3
Delphi panel scores (lowest score is 1, highest score is 5) for the extent to which sustainability issues are addressed within sustainability assessment tools for bioenergy systems.

Sustainability issues	C&I	LCA	EIA	CBA	SPA
Environmental dimension					
Air quality	2	5	4	4	2
Soil quality	4	2	4	1	1
Land use	3	3	3	3	5
Water quality	4	3	4	1	1
Water use	4	5	4	3	1
Biodiversity	3	3	3	1	1
Deforestation	4	3	3	1	3
Desertification	3	3	3	1	1
Landscape	2	4	4	2	1
Agrochemicals	3	3	3	1	3
Waste	4	4	3	1	1
Energy balance	4	5	3	5	5
Fossil resources	3	5	3	4	5
Social dimension					
Labour conditions	3	1	1	2	1
Human safety & health	3	1	3	2	1
Human rights	3	1	1	1	1
Access to resources	3	1	1	1	1
Food & energy supply	2	1	1	1	2
Capacity building	3	1	1	1	1
Democratic participation	3	1	2	1	1
Property rights	3	1	1	1	1
Fair trade	3	1	1	1	1
Social acceptance	3	1	3	1	1
Economic dimension					
Viability	3	1	1	4	1
Long term perspective	3	3	1	3	2
Reliability of resources	2	3	1	2	2
Reliability of technology	1	1	1	3	2
Risk minimisation	2	1	1	1	1
Local economy	3	1	1	1	1
Reliability of energy	2	1	1	3	3
Other desirable developments.	3	1	1	1	1
Institutional dimension					
Policy and legislation	5	1	5	1	2
Institutional capacity	2	1	2	1	1
Institutional well-being	3	1	1	1	1
Environmental management	3	1	2	1	1

issues [24]. Of the six selected tools, social issues are only addressed by C&I. The reason behind this is probably the difficulty with which social issues of sustainability are translated into measurable quantities, or at least into operational terms. According to Becker [1] approaches to quantification and operationalisation of social dimensions must be carefully restricted to those issues that can be described meaningfully by numerical or analytical tools and methods. Yet, C&I cover most of the issues of social sustainability although some sustainability issues such as labour conditions, human safety and property rights cannot get a better indicator than a rank or *go*/*no go*. Only for competition with food, no appropriate indicator was found yet in C&I. The institutional dimension is very poorly addressed in all of the tools except for the legislative aspect, which is of significant importance in EIA and C&I.

The Kruskal–Wallis analysis that was performed on the results of the sustainability issues for each of the sustainability sublevels (environmental, social, economic and institutional dimension) reinforced the visual conclusions by not revealing any significant differences between the tools except for the social dimension (*p*-values for the environmental, social, economic and institutional dimension are 0.014, 0, 0.011 and 0.009, respectively).

To find out which sustainability issues are addressed in EA, scientific literature was consulted. The relationship between exergy and sustainability is well explained in studies of Cornelissen [128], Rosen and Dincer [106], Dincer and Rosen [129] and Dewulf et al. [130]. It seems that the focus of EA is limited to the environmental dimension, in particular emissions and natural resource use. The authors state that environmental effects associated with emissions and resource depletion can be expressed in terms of one exergy-based indicator. In contrast with energy, which can never be lost as it is conserved according to the first law of thermodynamics, exergy can be lost due to internal irreversibilities. Therefore, sustainability is seen to increase and environmental impact to decrease as the exergy efficiency of a process increases [106]. Some studies were found relating EA and economics by determining the appropriate allocation of economic resources so as to optimize the design and operation of a system, or by determining the economic feasibility and profitability of a system. Examples of exergy-based economic analysis methods are thermoeconomics, second-law costing, cost accounting and exergoeconomics. Dewulf et al. [130] give a concise overview of the application of EA in the combined environmental and economic field, and debate the actual merits of such an exergy-based economic approach [101]. No exergy studies were found that address social issues of sustainability.

In general, the major problems in sustainability assessment are data availability and methodological agreement. For some sustainability issues, such as energy balance, methodologies are well defined and accepted, but for others, methodologies are heavily debated. For example, the ideas on how to inventory and characterize land use are incomplete and quite diverse [131], not only between tools but also within tools. In-depth discussions on how to integrate land use within LCA are still going on and can be found in [85,132–136] midst others. The same difficulties are faced for assessing biodiversity. Although a few indicators related to biodiversity already exist (e.g. species diversity, existence of threatened and protected species), there is no agreement on a common denominator or calculation procedure within sustainability assessment of bioenergy systems. At date, the problem is mostly tackled by determining protected areas where intervention is not allowed to take place. The reason why in most cost-benefit analyses some of the environmental and most of the social costs are omitted, is often because they are too difficult to estimate from an economic point of view and to translate into monetary terms. For the use of agrochemicals, for instance, cost-benefit analyses may consider the costs of treating wastewater from the chemical plant where the agrochemicals are produced, but the effect on nature is often omitted because it seems too complicated to determine the values for the deteriorated nature. It can be concluded that within existing assessment tools the same sustainability issues are often left out of consideration due to a lack of possible calculation methodologies or available data. Future research should focus on those sustainability issues for which no common calculation methodology could be defined yet.

3.2. Tool attributes

In the second evaluation step, tools were evaluated by the Delphi panel of experts on basis of their tool characteristics regarding use of data, followed procedure, reproduction of results, and use of the tool. Delphi scores ranged from 1 to 5, corresponding with very poor, poor, moderate, good or very good. The resulting data matrix can be found in Table 4. Some of the tool attributes are also of importance in the next level of comparison (overall model structure) and will be discussed in more detail there.

At first glance, no general differences can be observed between the tools. This perception is confirmed by the statistical Kruskal–Wallis analysis, which does not detect any significant differences between the different tools (*p*-values for data, procedure, results and use are 0.453, 0.220, 0.533, 0.192, respectively). Although there might not be a statistical significant difference in general, many smaller differences can be observed on the various aspects in particular.

Although input data is generally a difficult issue in sustainability assessment, LCA shows many advantages. Extensive high-quality data sets have been gathered in the past decennium and are regularly updated. CBA scores well because of advantages related to valuing such as a similar unit for all impacts which facilitates integration. Concerning data availability, need and integration, EIA shows difficulties. The tool is very site-specific and detailed, which requires extensive application of data and hampers integration. Low scores are also assigned to SPA, which has the disadvantage of being a very recent and not yet fully developed assessment tool. Only few sustainability issues are considered and clear assessment guidelines are still lacking. This might change in the near future.

On the aspects of procedure, C&I receives the best overall score. Indicators are simple and flexible measures, most often quantitative, that represent a state of economic, social and/or environmental development in a defined region. When selected with great care, C&I can be a strong measure for sustainability assessment. But in the case of poorly chosen indicators a variety of problems occur, amongst which overaggregation, measuring irrelevant aspects, dependence on a false model, deliberate falsification, and incompleteness [137]. Other advantages of C&I are an almost full coverage of the sustainability field, whereas other tools rather focus on one or two sustainability dimensions, and the ability to use static as well as dynamic data, whereas most other tools, except for EIA use only static data. A positive aspect to note, is that all tools score well on transparency and not any is prone to high subjectivity.

With regard to the results, all tools generally show high scores. Results are in most tools rather compact and clear, easy to understand without expert knowledge. Only for SPA one weakness can be observed for applying a complex calculation method which makes it difficult to interpret the results.

Finally, with respect to the use of the tool, all of them show the advantage of being able to integrate stakeholder input into the modelling, whereas accessibility forms a bottleneck for each of the tools. This means that expert knowledge is needed to apply the tool, particularly in the case of EIA and SPA. LCA scores best on time consumption and assistance considering the rather limited time that is needed for the assessment and the good guidelines and assistance that are available, the latter being the opposite for SPA. EIA seems to be worst on these two issues, as well when handiness is concerned.

Table 4
Delphi panel scores (lowest score is 1, highest score is 5) for tool attributes of sustainability assessment tools for bioenergy systems.

Tool attribute	C&I	LCA	EIA	CBA	SPA
Data					
Availability	3	4	2	3	2
Need	3	3	2	3	2
Type	3	5	5	5	5
Integration	4	1	1	4	1
Correctness	3	4	3	3	3
Procedure					
Flexibility	5	1	3	3	3
Coverage	4	1	1	4	2
Objectivity	3	3	4	3	3
Transparency	4	5	4	4	4
Validation	4	4	2	1	3
Time scale	4	1	1	5	2
State-of-the-art	5	5	5	3	2
Results					
Univocity	5	4	4	3	4
Simplicity	5	4	4	3	2
Type	3	5	4	4	5
Clarity	4	2	3	4	3
Communication	4	5	3	4	3
Use					
Flexibility	5	5	5	4	5
Accessibility	4	3	2	3	2
Application cost	3	3	3	3	3
Application field	5	3	4	2	4
Time consumption	3	4	2	3	3
Handiness	4	3	2	3	3
Assistance	3	5	2	3	2

3.3. Overall model structure

This part of the evaluation is based on literature review and the results can be found in the form of tool profiles in Appendix A. A discussion of the results follows here.

The *tool description* specifies in short what the overall purpose is of using the tool and which aspects are assessed. Although some tools are rather used for communication to provide others with information (C&I), whereas other tools serve as decision-support for operative or strategic decision making (CBA, EIA) or are used by companies for internal learning purposes (EA), or for all these purposes together (LCA, SPA), they all contribute in some way to sustainability assessment and can to some extend be used for the assessment of bioenergy systems.

The *tool concept* gives an overview of the different methodological steps that must be executed while applying the tool and is related to the *concept focus* of the tool. A tool typically consists of a systematic data and/or information gathering procedure and will often also include a calculation algorithm [123]. Tools that emphasise procedure are C&I and EIA, whereas the others tools (LCA, CBA, SPA and EA) rather focus on the computational algorithm. For example, the EIA methodology gives descriptions of an information gathering procedure (in order to make decision) in which various algorithms may be used, whereas the LCA methodology defines the type of computational model to be used (a computational model of material and energy flows related to a functional unit). Since procedure aims at describing the best way to reach a decision, while algorithms aim at finding the better solution, an analytical tool might be used as part of a procedural tool [125]. As a consequence of their focus on algorithm, analytical tools show the disadvantage that sustainability issues that cannot be modelled appropriately can hardly be integrated in the assessment. This again is related to the rather quantitative or qualitative character of the tool and will be discussed further on.

The *object of analysis* identifies the focus of decision. If the object of analysis is a project, such as a bioenergy implementation project, EIA or CBA is the natural choice rather than LCA or another method developed for another object, which could be preferred when assessing for example 1 MJ of biofuel. C&I as well as SPA and EA could lay their focus on any kind of object or system, be it a product, process or project.

Assessment tools usually involve *comparison* in various ways. The basis for comparison is what is being kept constant in a comparison [123] and depends in most cases on the object of analysis. For example, in LCA, all analyses are relative to the functional unit, which measures the unit good or service that is being delivered. In case of bioenergy this would be one unit of the fossil energy reference. The same applies for SPA and EA. C&I on the other hand is usually not used to make a comparison between different products or projects, but rather to make an evaluation of the same project over time. EIA does not necessarily require a reference object either, however, in most EIA studies, various alternative projects are compared amongst which a zero alternative [89]. This is also the case for CBA.

The degree of *standardisation or harmonisation* is an important factor because even small differences in methodological factors can influence the results. Of all the tools selected for this study, LCA is the only tool that is standardised by the ISO. The tool evolved over the last three decades from a relatively vague framework for conducting assessments, into a rigorous set of internationally standardised ISO guidelines [71,72,123,138]. However, Dewulf and Van Langenhove [109] state that some further methodological developments are still needed for the LCIA models and methods. For C&I, internationally harmonised frameworks and/or guidelines exist for specific systems, often as part of certification systems. Also for bioenergy, different C&I frameworks have been developed [52–54,121]. According to Moberg [95] an international agreement on a general procedure exists for EIA and because of legal implementation, many countries defined their own harmonised procedure. Also for CBA, international guidelines exist. For example, the European Union established an extensive guide for CBA of different kinds of investment projects [139]. On the methodology of SPA, little information is available because of very recent development of the tool. For EA, no standardisation or harmonisation has been performed but quite some information is encountered regarding the methodology [104,105,107,110,140].

Similarity can be found between the degree of standardisation or harmonisation and the *frequency of use*. With respect to sustainability assessment of bioenergy systems, LCA is one of the most well-known and applied tools, together with C&I within certification systems. CBA, in its turn, seems to be the most well established and utilised tool in economic decision making [95]. EIA is a well-known and frequently used tool for site-specific investment projects where participation of all the stakeholders involved is of great importance. To date, SPA is only used by its developers. And although many scientists suggest that the impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed by considering exergy [105,113,141], the EA tool still is not very frequently applied in a non-scientist environment, perhaps due to the unfamiliarity with the exergy concept.

With regard to the *time perspective*, C&I is generally seen as a retrospective tool, whereas CBA, EIA and SPA have mainly prospective purposes, and LCA and EA can be considered as both retro- and prospective. Concerning the temporal and spatial scale, these aspects are in principle defined by the temporal and spatial distribution of the assessed impacts of the system under evaluation. Therefore, sustainability indicators within C&I can be divided roughly into state and trend indicators and have specific spatial scales and time horizons. Becker [1] presents a clear overview of sustainability indicators in a space/time frame. In agriculture, spatial scales range from plot-level and small-scale gathering to agribusiness and large plantations, and temporal scales range from short-season crops to perennials and long rotations in swidden agriculture [142]. While conventional environmental assessment techniques such as EIA focus only on either manufacturing processes or end-of-life disposal (or reuse), LCA considers the life cycle of a system, or the entire chain of events and activities that are necessary to support the product or process [71,138,143]. This is often called the cradle-to-grave approach, and has the obvious advantage of revealing potentially significant but hidden environmental impacts. Instead of focussing attention on large, concentrated and readily apparent point sources of impacts – for example, a manufacturing plant – LCA also takes into account dispersed activities whose cumulative effects may prove to be critical as well [138]. In many cases, EA takes on a life-cycle perspective as well, quantifying the cumulated exergy consumption of a product or process from “cradle to grave”. In this regard, it is similar to LCA. Moreover, according to Dewulf et al. [101] EA can be part of an LCA, representing a method for the life-cycle impact assessment of resource consumption. A coupling of Exergy Analysis and life cycle inventory databases (e.g. Ecoinvent), has been put into practice by the authors. The developers of SPA followed another train of thought considering geographical system balances of resources and related effects rather than a life-cycle approach, what makes the assessment a snapshot in time rather than an integration of impacts that occur over time, and no future developments are taken into consideration. A cost-benefit analysis can give useful results for the present costs and benefits, but future benefits are strongly dependent on the interest rate applied in the analysis. Jørgensen [103] state that the use of depreciation of future benefits due to introduction of an interest rate will inevitably emphasize too much present benefits. In addition, predictions on future interest rate have a very high uncertainty.

The *spatial scale* is related to the spatial boundaries and the spatial horizon of the analysed system. Whereas most of the selected tools can be applied on different spatial scales, EIA is a particularly site-specific tool [125]. Although all the tools make use of environmental data, the environmental data of EIA are usually more detailed and site or project specific. For example, EIA can often involve taking into account the duration and concentration of emitted pollutants and the assessment of actual impacts on the environment [123], whereas the other tools keep it less situation-specific to serve as rather generic tools. The site-specificity of EIA makes it a time and resource demanding tool. On the opposite side, indicators, and in particular social indicators, can be used to refer to all levels of the spatial hierarchy, with varying degrees of relevance. Yet, in different societies with varying cultural and legal practice, assessment of social indicators will always be a complex issue that cannot easily be put into operation [1].

There is no straightforward answer whether an assessment tool should be purely quantitative or both *quantitative and qualitative*. Not all sustainability issues can easily be quantified. The accuracy of the outcome strongly depends on the accuracy of the measurements and the modelling within the tool. Besides, the combination of qualitative and quantitative results impedes aggregation into one single outcome. Therefore, in some tools only well-defined quantitative parameters are counted in. On the other hand, in order to fully address sustainability, all issues should be considered, also the non-quantifiable ones. Of all the tools regarded in this study, only C&I and EIA have both a quantitative and qualitative character. The other tools are purely quantitative.

The quantitative and/or qualitative character of a tool also influences the way in which the *results* are reproduced. According to Becker [1], three basic approaches can be distinguished: unranked lists of heterogeneous indicators, scoring systems with unified dimensions, and system descriptors. C&I, LCA, EIA and SPA belong to this first group, although results might be partially aggregated for example into impact categories as is the case in LCA. The advantage of listing results as heterogeneous indicators gives the advantage of transparency, but the disadvantage of complex interpretation. Because of their ability to transform all parameters into one unit, CBA and EA are tools that belong to the second group of scoring systems with unified dimensions. Such tools have the advantage that they permit comparison of and calculation with different quantities in a uniform dimension. However, according to Becker this assumes a congruent basis of calculation, which in reality differs considerably depending on the underlying value judgement. Furthermore, in case of CBA monetary values are not sufficiently consistent with ecosystem structure and function, and therefore their aggregation may lead to inadequate environmental decisions.

The assignment of *weight scores* is considered as a very controversial step mainly because it involves social political and ethical value choices [109]. Therefore, weighing of impacts is in most tools not integrated, or indicated as an optional step. For example, in the inventory phase (LCIA) of LCA, a number of methods is proposed to conduct weighing. These methods are divided in two general groups: (1) problem-oriented approaches and (2) damage-oriented methods. Examples of the problem-oriented approaches are the CML-method and EDIP method, and examples of damage-oriented methods are EPS 2000 and Eco-Indicator 99. The IMPACT 2002+ method attempts to link the problem- and damage-oriented approaches in a common framework [109].

An optimal application of a model or tool requires the execution of a *sensitivity and uncertainty analysis b*efore the final conclusions and recommendations of the study are made. However, because of time and/or resource restriction, this part is often omitted. Of the six tools considered in this study, only two of them, LCA and CBA, include a sensitivity analysis and to a limited extend also an uncertainty analysis in their methodology, however optional. Only in a few case studies sensitivity and/or uncertainty analyses were conducted although it was often stated that the methodology applied was prone to considerable uncertainties. With regard to assessment tools in general, three kinds of uncertainty can be distinguished: data uncertainty, model uncertainty and scenario uncertainty. Small-scale models are less prone to uncertainty than large-scale models, because the latter cover in most cases longer time spans, and therefore need to make more probability assump-

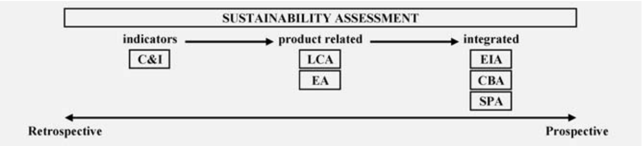

Fig. 2. Possible field of application of sustainability assessment tools based on their temporal focus, along with the object of focus of the tool.
Adapted from Ness et al. [15].

tions [1]. More specific, in case of C&I uncertainties can be caused by the diversity of the set of criteria and indicators, criteria content, indicator quality, lack of validity, poor data sets amongst others [144]. In life-cycle assessment, various aspects such as input parameter values, system boundaries, allocation procedure, and fossil reference system, give rise to wide ranges of results [83]. In a cost-benefit analysis the accuracy of the outcome highly depends on which costs are included in the analysis and how accurately costs and benefits have been estimated. Various peer-reviewed studies [145,146] show that differences between actual costs and benefits and estimated costs and benefits can be up till more than fifty percent and that the outcomes of cost-benefit analyses should be treated with caution because they may be highly inaccurate. Furthermore, Flyvbjerg et al. [147] state that inaccurate cost-benefit analyses may be argued to be a substantial risk in planning, because inaccuracies of the size documented are likely to lead to inefficient decisions. EIA is prone to similar uncertainties as in C&I in the phases in which indicators are used and to some extend to the same uncertainties of CBA in case a financial analyses is executed. For SPA, no information was found on the risk of uncertainty while applying the tool. In EA at last, a certain degree of uncertainties is found in exergy estimations of products and processes.

3.4. *Application of tools*

In the fourth and last level of the evaluation, an approach was followed in which two factors are considered: temporal characteristics and focus area. As is discussed earlier in this paper, temporal characteristics evaluate the time frame wherein a product or projects has an impact, as well as the time perspective applied to the object analysed which can be retrospective or prospective. The former is accounting/monitoring, keeping record of progress, which can be useful when searching for preferable changes in for example production, behaviour or policies and to indicate sustainable development. Prospective approaches, on the other hand, are seeking to predict future situations and can thereby facilitate comparison between different new products, plans, etc. [123]. The focus areas can be (1) indicators and indices, which can be further broken down into non-integrated and integrated, (2) product-related assessment tools with the focus on the material flow and/or energy flows of a product or service from a life cycle perspective, and (3) integrated assessment, which are tools usually focused on policy change or project implementation. Fig. 2 gives an overview for the six tools regarded in this paper. As stated by Ness et al. [15] indicators and indices (i.e. aggregated indicators), which are continuously measured and calculated, allow for the tracking of longer-term sustainability trends from a retrospective point of view. Product-related tools such as LCA and EA allow both retrospective and prospective assessments. Integrated assessment tools like EIA, CBA and SPA are mostly used for supporting decisions related to a policy or a project in a specific region and have an ex-ante focus. Many of these tools are based on systems analysis approaches and integrate environmental and society issues.

Besides the area of applicability, a categorization of tools can also be made concerning their development and frequency of use. For LCA, CBA and EIA, there are relatively well established, transparent and generally agreed guidelines available, whereas for C&I and for EA the practitioner is free to use a personal interpretation of the general principles. Newer tools such as SPA represent an area where guideline establishment is still in early developmental stages.

3.5. *Integration of existing tools*

As can be concluded from the previous analysis, the various existing sustainability assessment tools are not necessarily complementary, but some of them may be well combined in practice in the form of a toolbox. For the assessment of bioenergy systems, impacts must be considered both in short and long term and it involves tracking on-going activities (the accounting approach), as well as choosing between alternative materials/products/actions (the project approach). The former is important for the generation of alternatives, the latter for the comparison of alternatives. Therefore, tools that focus on the former (i.e. analytical tools such as LCA, CBA, SPA and EA) might be used as part of a tool that focuses on the latter (i.e. procedural tools such as C&I and EIA). As the procedure of C&I seems to be more clear, transparent and efficient compared to this of EIA, it would be recommended to use the procedural framework of C&I within the toolbox. Nevertheless, EIA also has some very useful procedural parts such as the screening process and mitigation of negative impacts, which could be integrated into the C&I framework. With regard to the analytical part of the toolbox, the LCA methodology stands out for its well-developed and clear assessment of environmental impacts, although EA could be a decent alternative for the calculation of energy efficiencies. Where economic sustainability indicators are concerned, CBA seems to be the most useful tool to provide calculation algorithms, although many issues in this sustainability dimension for which no common calculation algorithm exists yet will require considerable additional research efforts. In the social sustainability field, the most useful calculation procedures are encountered in the C&I methodology, however also in this field commonly accepted calculation procedures are still lacking for various sustainability issues.

Even more interesting would be the construction of a combined software toolbox, which includes an application of geographic information systems (GIS) and remote sensing for determining spatial characteristics, together with a model that assesses the temporal dimension of impacts, as well as a methodology to conduct sensitivity and uncertainty analysis, and finally also an instrument which enables decision makers to weight sustainability issues and compare alternatives against each other. It is clear that, for such a tool to be created, far more research has to be conducted. Scientists of many different fields of expertise have to combine their knowledge and forces. Solutions must be found for those sustainability issues for which no methods can be recommended yet. Besides, this paper represents only a small selection of sustainability assessment tools. It would be recommendable to extend this study to other assessment methodologies such as Multi-Criteria Analysis, Risk Assessment, Strategic Environmental Assessment, Social Impact Assessment, Ecological Footprint, Life Cycle Costing, and many more.

4. Conclusions

The use of biomass for energy as part of a sustainable development strategy is heavily debated due to many concerns about sustainability. Bioenergy systems are complex systems having an impact on various levels of nature and society and involving many stakeholders. Furthermore, sustainability is an essentially contested notion because it is inherently complex, normative, subjective and ambiguous [18]. As a consequence, sustainability assessment of bioenergy systems is a highly demanding and complicated task. Nevertheless, many researchers have been engaged in a quest to develop tools and methods to tackle this difficult job. While many started working from a mono-disciplinary basis, others made an attempt to develop generic tools and instruments. This has resulted in a diverse field of approaches [23]. This paper tried to give a better insight in the complex world of sustainability assessment of bioenergy systems by analysing and comparing the applicability and performance of a number of basic sustainability assessment tools that can be applied in this sense. First, a framework was constructed for the evaluation of the selected assessment tools, which takes all issues into account that are of importance for assessing bioenergy. In the second step a Delphi panel of experts was consulted, as well as a considerable amount of literature. In the third step, results were analysed and shaped in comprehensible forms. It can be concluded that not any of the selected assessment tools is judged as completely satisfying on all aspects of the evaluation framework. Although some tools are already very well developed, they all have severe shortcomings for sustainability assessment of bioenergy, whether it is from a theoretical point of view and/or from the practical side. Especially the absence of appropriate indicators and calculations of a number of sustainability issues, as well as the lack of data and uncertainty analysis, are often problematic. For the moment, not any of the selected tools could be recommended to perform an overall and integrated sustainability assessment of bioenergy systems. It appears that, in the first place, a good definition of the sustainability problem is crucial. A different assessment focus may lead to a different choice of assessment tool. Furthermore, all tools display particular advantages and disadvantages, which means that trade-offs are inevitable and a balance must be found between scientific accuracy and pragmatic decision making. LCA, for instance, performs undoubtedly better on the environmental part of sustainability while CBA is a better choice with respect to assessing economic issues. EIA shows quite some resemblance to LCA in terms of basic equations, and addresses even more sustainability issues, but the site-specific character of the tool makes it very time and resource demanding. C&I is probably the most practical and frequently used tool, but as is the case for EIA, the assessment results in a list of parameters with varying units which makes it difficult to interpret. EA seems to be a worthy alternative for LCA but the tool appears to be rather difficult to interpret and is so far not often practised for sustainability assessment. CBA in turn is praised for its simple results and its suitability for comparison, but monetisation is a source of subjectivity and uncertainty, and reduces transparency. SPA for its part follows an interesting approach that is completely different from the others looking at perturbations in a system instead of a products life cycle, but the early developmental stage of the tool impedes a generic use.

In addition, it can be concluded that the various existing assessment tools are not necessarily complementary, but might be combined in practice in the form of a toolbox. It would thus be interesting to investigate the possibility of creating a toolbox that combines the clear and transparent procedure of C&I with some interesting procedural parts of EIA such as screening and mitigation, supplemented with calculation algorithms of LCA and CBA for respectively environmental and economic sustainability indicators. Therefore, a more comprehensive interdisciplinary approach is necessary to align the different tool characteristics and focuses, together with additional research on those sustainability indicators for which no common calculation procedure could be developed yet.

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Appendix A.

See Tables A1–A6.

Table A1
Tool profile of Criteria & Indicators (C&I).

General	
Tool description	Criteria and Indicators (C&I) are a policy and management tool used to define, assess and monitor progress towards sustainable management in a given area, over a period of time taking into consideration the environmental, social, economic, cultural and spiritual needs of the full range of stakeholder groups in the areas concerned [49].
Tool concept	After the definition of goal and scope, a conceptual framework is developed that is generic and broadly applicable. The framework is divided into principles, criteria, indicators and metrics and/or verifiers. For those issues for which no indicators are currently available, reporting protocols can be formulated. Eventually, indicators are assessed and verified. Criteria define the essential elements against which sustainability is assessed. Each criterion relates to a key element of sustainability, and may be described by one or more indicators. Indicators are parameters which can be measured and correspond to a particular criterion. They measure and help monitor the current condition and change over time in quantitative, qualitative and descriptive terms [49]. Metrics and verifiers provide additional data or information that enhances the specificity of the ease of assessment of an indicator.
Object of analysis	C&I can be used to assess all kinds of systems on different levels, although higher levels are less frequently used (national, supranational, global). For example, in the case of agricultural land use systems, the system under consideration can be the cropping system (plot level), farming system (farm level), watershed/village (local level), landscape/district (regional level) or a hierarchy of different levels can be used [1].
Type of comparison (between alternatives, within a studied system, against a reference)	C&I is mostly used in an absolute way (no comparison of different systems or scenarios), although C&I may also be used to monitor a system over time.
Standardisation/harmonisation	There is no standardisation, but various initiatives have tried to develop internationally harmonised C&I frameworks, for example in sustainable forest management or sustainable palm oil production [50,60].
Frequency of use	C&I is a very frequently used tool because of its ease of use, flexibility and transparency. The International Institute for Sustainable Development (IISD) provides an overview of currently about 600 indicator initiatives including the type of initiative, the nature of public involvement, geographic scope and project goals [148,149].
Methodological	
Time frame (retro-/prospective and temporal boundaries)	As a monitoring tool, C&I is retrospective, which can be useful to search for preferable changes and to indicate sustainability. On indicator level, a difference can be made between trend indicators and state indicators. Trend indicators capture the dynamic aspect of sustainability over time (e.g. yield trends, depletion rate) whereas state indicators reflect the condition of the respective (eco)system [1].
Spatial scale (spatial boundaries)	C&I can be applied at different levels: management level, regional, national [49]. Also on indicator level, there are multiple spatial scales depending on the indicator used [54]. An example on small spatial scale is the yield trend and on large spatial scale is the discount rate of resource depletion [1].
Procedure/algorithm focus	Procedure focus.
Quantitative/qualitative	Both quantitative and qualitative.
Results (listed or aggregated)	Results are listed with different units, but an indicator might be an aggregation of different effects (e.g. GHG balance).

Table A1 (*Continued*)

Weight scores

There is no weighing methodology included in C&I. In some cases, Multi Criteria Analysis (MCA) is used to weight and aggregate results.

Sensitivity & uncertainty

There is no sensitivity nor uncertainty analysis included in C&I although the tool is subject to many uncertainties caused by the diversity of the set of criteria and indicators, criteria content, indicator quality, lack of validity, poor data sets amongst others [144].

Table A2

Tool profile of Life Cycle Assessment (LCA).

General

Tool description

Life Cycle Assessment (LCA) assesses, in a systematic way, the environmental issues and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope [71].

In a bioenergy perspective, LCA is mostly used to conduct an energy and GHG balance.

Tool concept

There is no single method for conducting LCA. Organizations have the flexibility to implement LCA as established in the International Standard, in accordance with the intended application and the requirements of the organization [72].

The ISO standard defines 4 steps: (1) Goal and scope definition (defined by ISO 14041 [150]); (2) Inventory analysis (LCI, defined by ISO 14041 [150]); (3) Impact assessment including classification, characterisation and valuation (LCIA, defined by ISO 14042 [151]); (4) Interpretation (defined by ISO 14043 [152]) or improvement assessment [117].

Object of analysis

Products and services.

Type of comparison (between alternatives, within a studied system, against a reference)

LCA is a relative approach, which is structured around a functional unit. This functional unit defines what is being studied. All subsequent analyses are then relative to that functional unit, as all inputs and outputs in the LCI and consequently the LCIA profile are related to the functional unit.

Standardisation/harmonisation

The LCA methodology is standardized by the ISO 14040–14043 [71,150–152].

Frequency of use

LCA is one of the most frequently used systems analysis tools.

Methodological

Time frame (retro-/prospective and temporal boundaries)

LCA may be used prospectively when used for development of new products, strategies, etc. and retrospectively when used to improve processes and products, for purchasing decisions, etc. [95].

LCA takes the whole lifetime of a function in account. The depth of detail and time frame of an LCA may vary to a large extent, depending on the goal and scope definition.

Time is an important factor in calculations of the annual life-cycle performance of biofuels. Both energy inputs and outputs and emissions occur at different points in time. For example emissions from land use due to changes in aboveground biomass occur mainly during the short period when the land is converted for cultivation. The chosen time scale for amortization of these emissions can change the results drastically. The IPCC uses a default value of 20 years while Greenpeace aims for a 10-year period [82].

Spatial scale (spatial boundaries)

Since the assessment is not site-specific, there are no geographical boundaries [95].

LCA can be used by governments, private firms, consumer organisations, and environmental groups as a decision support tool. The scope of the decisions covered by LCA ranges from broad management and policy choices to specific selection of product or process characteristics during design [138].

Procedure/algorithm focus

Algorithm.

Quantitative/qualitative

Quantitative.

Results (listed or aggregated)

In the LCIA phase, LCI results are assigned to impact categories. For each impact category, a life cycle impact category indicator is selected and the category indicator result (indicator result) is calculated. It is this list of indicator results (LCIA results or LCIA profile) that provides information on the environmental issues associated with the inputs and outputs of the product system [71].

Table A2 (*Continued*)

Weight scores

Weighing of impacts is an optional step in the LCIA phase. A number of methods exist, divided in two general groups: (1) problem-oriented approaches and (2) damage-oriented methods. Examples of the problem-oriented approaches are the CML-method and EDIP method. Examples of damage-oriented methods are EPS 2000 and Eco-Indicator 99. The IMPACT 2002+ method attempts to link the problem- and damage-oriented approaches in a common framework [109].

Using the ISO standard, the valuation step is not allowed for external studies since there is no scientific basis for reducing LCA results to a single overall score or number because weighing requires value choices.

Sensitivity & uncertainty

Sensitivity analysis is part of the fourth LCA stage in ISO [71].

Although various aspects such as input parameter values, system boundaries, allocation procedure, and fossil reference system, give rise to wide ranges of results [83], no uncertainty analysis is included in the ISO.

Table A3

Tool profile of Environmental Impact Assessment (EIA).

General

Tool description

Environmental Impact Assessment (EIA) is used to evaluate potential environmental impacts – considering natural, social and economic issues – that a proposed project may have, with the aim to reduce the negative effects [89].

Tool concept

More than 100 countries worldwide have EIA systems. They vary greatly in terms of procedure and practice. The scope and methodologies of EIA have evolved greatly over the past decade. Advances include consideration of biodiversity and climate change issues; increasing applications to policy, plans and other strategic decisions; and review of trade, privatisation and structural adjustment initiatives [24].

Although the amount of steps in an EIA process may differ, in general the following steps can be distinguished: (1) Screening; (2) Scoping; (3) Impact assessment; (4) Mitigation; (5) Reporting (EIS); (6) Reviewing; (7) Decision-making; (8) Implementation [24].

EIA is very site-specific. Most countries have lists of activities for which EIAs are required (e.g. mining or major construction works). In addition, some countries have identified sensitive environments (e.g. estuaries of cultural heritage sites) for which EIAs are needed [24].

Stakeholder participation is an important issue in EIA.

Object of analysis

A policy, plan, programme or (mainly) a project.

Type of comparison (between alternatives, within a studied system, against a reference)

Comparison is based on the project or site being analysed. There is no obvious need for a reference object, since the purpose of the tool is to describe the effects a planned action will have. However, EIA should consider alternatives to the proposed project localisation and design, including the zero alternative [95].

Standardisation/harmonisation

There is an international agreement on general procedure [95]. Often countries have their own procedure.

Frequency of use

EIA is a well-known and frequently used tool. EIAs are performed in several countries including some developing countries [95].

Methodological

Time frame (retro-/prospective and temporal boundaries)

Prospective, foresees impacts of planned activities and improves long-term viability of projects [95].

For a major project, an EIA may take considerable time, manpower and resources. The first 2 stages are very important to determine the required extent and focus of the EIA [153].

Spatial scale (spatial boundaries)

(Same as time frame) The spatial boundaries are defined by the spatial distribution of important direct and indirect impacts caused by the proposed project or plan.

Procedure/algorithm focus

Procedure focus.

Quantitative/qualitative

Both quantitative and qualitative.

Results (listed or aggregated)

Listed with several different units. EIA reports tend to present impacts in separate chapters for environmental, social and economic aspects [153].

Table A3 (*Continued*)

Weight scores

No available information on the use of weight scores.

Sensitivity & uncertainty

No sensitivity or uncertainty analysis is included in the EIA procedure.

Table A4

Tool profile of Cost Benefit Analysis (CBA).

General

Tool description

Cost Benefit Analysis (CBA) is a method trying to estimate the total impact of a project on society by calculating social costs and benefits. Environmental impacts are included by valuation of these, converting them into monetary terms [94].

Tool concept

Steps: (1) identification of problem and alternative solutions; (2) identification of social costs and benefits for each alternative; (3) valuation of costs and benefits (usually in monetary terms); (4) allocation of costs and benefits over the project time; (5) calculation of net present value (NPV); (6) ranking alternatives by NPV; (7) sensitivity analysis should be performed; (8) presenting recommendation [94].

Object of analysis

Projects (or sometimes decisions on higher strategic levels e.g. programmes) [95].

Type of comparison (between alternatives, within a studied system, against a reference)

The zero alternative is used as reference and different alternatives should be compared [95].

Standardisation/harmonisation

CBA follows an established methodology. Rough guidelines are available [94].

Frequency of use

CBA is the most well established and utilised tool in economic decisions situations [95].

Methodological

Time frame (retro-/prospective and temporal boundaries)

Prospective: estimation of future costs and benefits.

Future generations should be considered, which implies no theoretical time boundary [95]. Preference of time is considered through discounting, which is a way of including the change of capital over time. Discounting is done by deciding on a discount rate defining present values of future costs/benefits.

Spatial scale (spatial boundaries)

Economic and geographical boundaries are set according to the development considered in the CBA study. CBA is a partial economic analysis with no feedback from other markets or regions [95].

Procedure/algorithm focus

Algorithm focus.

Quantitative/qualitative

Quantitative.

Results (listed or aggregated)

Results are in monetary unit. Costs and benefits that are impossible to calculate in monetary terms may be presented as intangibles [95].

Sometimes Multi-criteria Analysis (MCA) or Social Impact Analysis (SIA) is used to count for the intangible costs and benefits in the final result.

Weight scores

Valuation of costs and benefits or the use of MCA or SIA may involve some kind of weighing.

Sensitivity & uncertainty

A sensitivity analysis is included in the procedure of the tool (step 7) but not necessarily performed.

CBA is subject to huge uncertainty because of many valuations. Since the result is presented in an aggregated form, this uncertainty may often be forgotten [95].

Table A5

Tool profile of Exergy Analysis (EA).

General

Tool description

Exergy Analysis (EA) is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change. The exergy method is a useful tool for furthering the goal of more efficient energy-resource use, as it enables the locations, types and magnitudes of wastes and losses to be identified and meaningful efficiencies to be determined [129].

Table A5 (*Continued*)

Tool concept

Exergy can be accounted for both in energy and material. It can describe loss of natural resources in physical terms [154]. Due to entropy generation, the energy that can be made available from the outputs (exergy embodied in outputs) is less than the energy that can be made available from the inputs (exergy embodied in inputs), although the total energy of the outputs equals the total energy of the inputs. This quality degradation takes place in all physical and chemical processes, whether they take place in the natural ecosystem (production of biomass, . . .) or in the industrial ecosystem (production, consumption, . . .) and it is quantifiable by the loss of exergy. For sustainability assessment of products and production pathways, three interacting sections are taken into account: the production and consumption chain, processes within the natural ecosystem and processes in the industrial metabolism [109].

Steps: (1) estimation of energy input to the system; (2) calculation of exergy input (each energy contribution is multiplied by its energy quality (exergy) factor); (3) estimation of energy output from the system; (4) calculation of exergy output (as 2); (5) output is divided with input and the exergy ratio is obtained [154].

Object of analysis

Products, projects and also economies [95].

Type of comparison (between alternatives, within a studied system, against a reference)

The results of EAs are always relative to the specified reference environment, which in most applications is modelled after the actual local environment [106]. An EA study can serve to obtain absolute exergy values of products and processes as well as to compare alternatives to find the more exergy efficient one [95,101].

Standardisation/harmonisation

No harmonisation of standardisation.

Frequency of use

To some extent used in a rather expertised environment. Mostly used for optimisation of energy processes. In recent literature, the exergy concept has been shown to be a powerful tool in the sustainability assessment of technology and in the analysis of bioenergy systems [102].

Methodological

Time frame (retro-/prospective and temporal boundaries)

Prospectively for estimating the efficiency of potential developments and retrospectively for searching potential beneficiary changes [95].

No temporal boundaries. In many cases, Exergy Analysis methods take on a life-cycle perspective, quantifying the cumulated exergy consumption of a product or process from “cradle to grave” [101].

Spatial scale (spatial boundaries)

Geographical boundaries are stated according to the object under study [95].

Procedure/algorithm focus

Algorithm focus.

Quantitative/qualitative

Quantitative.

Results (listed or aggregated)

Results are aggregated and expressed in Joule of exergy.

Weight scores

No need for weighing factors by using one single unit that is physically interpretable and stable with time [101].

Sensitivity & uncertainty

Sensitivity and uncertainty analyses of EA results were performed by Dewulf et al. [101,155].

Table A6

Tool profile of System Perturbation Analysis (SPA).

General

Tool description

System Perturbation Analysis (SPA) identifies the best usage of limited resources such as land, wood waste or imports, in terms of fossil energy savings or GHG emissions within a given system.

Tool concept

A system is defined in which the possible scenarios take place.

Conversion routes (resource-conversion-product), utilities, and targets are taken into account.

Each SPA scenario is actually a set of perturbations of resources and targets. For each perturbation impacts are calculated.

Object of analysis

Products, projects and economies.

Table A6 (*Continued*)

Type of comparison (between alternatives, within a studied system, against a reference)	In an SPA study, alternatives are compared to a reference scenario (actual scenario or zero alternative).
Standardisation/harmonisation	No standardisation and very little information on the SPA methodology is available.
Frequency of use	SPA is recently developed and to date only used by the developers [115,116].
Methodological	
Time frame (retro-/prospective and temporal boundaries)	Prospective, foresees impacts of possible projects, products or processes. SPA takes the whole lifetime of a function into account.
Spatial scale (spatial boundaries)	SPA considers a given system where resources are transformed into products through a given conversion route. Examples exist already for regional or national systems [115] and for single processes [116].
Procedure/algorithm focus	Algorithm focus.
Quantitative/qualitative	Quantitative.
Results (listed or aggregated)	Listed, expressed in several different units.
Weight scores	No use of weight scores.
Sensitivity & uncertainty	No information was found on any sensitivity or uncertainty calculations, but in the study of Delattin et al. [116] an error calculation was made.

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