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Research paper

An approach to unify the appraisal framework for biomass conversion systems

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ABSTRACT

The need for a unified appraisal framework for biomass and bioenergy has been extensively discussed in literature. It is emphasized that a working unified appraisal framework can essentially improve bioenergy policymaking by offering a structured and transparent approach to tackle the *bioenergy trilemma* and to work out whether or not a certain biomass conversion technology or system should be implemented (always in direct comparison to others). Further, such an approach could be used to better examine the interdependencies of the single elements of the *triple bottom line of sustainability* (economy, environment, society). This also would lead to the improvement of existing and future policies and would give bioenergy a better foundation within the ethical debate by transparently showing the trade-offs between economy, environment and society. This paper drafts a unified appraisal framework for biomass conversion systems that integrates different approaches on the data, impact and decision making level. On the bottom line the proposed architecture in total addresses all relevant requirements from literature and fits well into the valuable work that has been done previously.

1. Introduction

The need for a unified appraisal framework (UAF) for biomass and bioenergy has been extensively discussed in literature [1–4]. It is emphasized that a working UAF can essentially improve bioenergy policymaking by offering a structured and transparent approach to tackle the *bioenergy trilemma* [5] and to work out whether or not a certain biomass conversion technology or system should be implemented (always in direct comparison to others). Further, such an approach could be used to better examine the interdependencies of the single elements of the *triple bottom line of sustainability* (economy, environment, society) [4]. This also would lead to the improvement of existing and future policies and would give bioenergy a better foundation within the ethical debate by transparently showing the trade-offs between economy, environment and society [1,6].

It has been shown that in recent years numerous appraisals of biomass conversion systems have been done to progress this task [3]. Liew et al. [2] discovered that within these tries a typical process pattern is applied regularly. This pattern starts with the evaluation and modelling of the technical background of the technologies or value chains on scope (data level), which is followed by an impact assessment by relevant tools (impact level – based e.g. on the *triple bottom line approach*), and closed by the application of a scoring model (almost Multi-criteria Decision Making approaches) to rank the relevant alternatives (decision making level).

Within an extensive literature review Boucher et al. [3] selected 20 key assessment reports out of more 1300 sources that already came close to an UAF. They defined that UAFs are formulated as "strategies and/or standardized procedures for gathering, prioritising and communicating information about biofuels, involving analysis and judgement, and meant to support decision-making or policy forming". It was assessed to which extend the selected key assessment reports addressed impartiality, transparency, participation (of lay people, experts and stakeholders), and scientific evidence basis, focus on uncertainties, and explicit values and ethics. It was found that especially impartiality, scientific evidence basis and transparency were the most important appraisal properties applied. However, participation of lay people and stakeholders as well as the embedment of explicit values and ethics in the decision process was found to be weak for almost all of them. The authors

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recommended focusing less on the details of the single building-blocks of a UAF but rather on how existing methods and knowledge can better be integrated for further research [3].

For the years following the review of Boucher et al. (which ends in 2011) a number of relevant assessment papers from peer-reviewed journals can be identified [7–14]. Only a few of them are really combining the triple bottom line with a standardized procedure for strategic decision making and policy support. In this regard the works of Santoyo-Castelazo and Azapagic [7], Diaz-Chavez [11], Fontanta et al. [9], and Gnansounou [12] are specially worth noting.

Gnansounou [12] presented a logic-based model for the sustainability assessment of biofuels by a hierarchical structure. The strengths of the approach presented are intrinsic transparency and simplicity. However, its hierarchical structure forms the main weakness which implies independency of the different indicators. Fontana et al. [9] presented a systematic framework that included the ecosystem services as criteria into a *multi-criteria decision making (MCDM)* approach. The advantage of this approach is its flexibility and the involvement of explicit values and ethics. However, the use of the software PROMOTHEE makes the procedure less transparent and lay people are also excluded from the weighting procedure [3]. Diaz-Chavez [11] proposed an appraisal framework based on matured environmental management tools for data gathering as well as on the triple bottom line. The approach is scientific evidence based, and includes explicit values and ethics. However, it leaves out to define a weighting procedure as well as a procedure for data aggregation with respect to decision making.

Santoyo-Castelazo and Azapagic [7] presented a decision-support framework for energy systems in general that integrates the triple bottom line and aggregates decision making data with a MCDM approach. Although this approach seems to be the most elaborate integrated appraisal framework in the context of energy system assessments, it does whether define guidelines for data gathering, category and criteria selection, nor a procedure for the weighting of the sustainability indicators used. Moreover, criteria are preselected and the approach is lacking in transparency due to a missing description of the data processing methods and a visualisation procedure.

Considering these findings, this paper drafts a UAF for biomass conversion systems that integrates different approaches on the data, impact and decision making level. On the bottom line the proposed architecture in total addresses all relevant requirements from literature and fits well into the valuable work that has been done previously.

2. Material and methods

The following sections describe the architecture of the UAF. Although the approach can be adapted for any other decision problem, the scope of this work is the assessment of biomass conversion systems, for which it specifically has been developed. The approach relies on data input (foundation – data level) that is fed into a tripartite assessment process (pillars – impact level), covering economic, environmental and societal aspects. Results of the assessments are integrated and evaluated through the use of an appropriate Multi-criteria decision making (MCDM) methodology (rooftop – decision level, compare Fig. 1).

2.1. Technology design assessment – the data level

A review of the literature on bioenergy systems assessment [15–22] shows that technical criteria are often directly incorporated into the assessment of bioenergy conversion systems and treated equally to other assessment criteria e.g. from the triple bottom line. Such an approach can easily introduce a bias towards technological properties, since most criteria found within the triple bottom line are proxies for basic technical criteria (e.g. like energy efficiency, reliability and maturity). To avoid such double counts, our UAF is built-up differently.

As depicted in Fig. 1, the UAF is in its first step based on a comprehensive technological assessment called *Technology Design Assessment* (TDA). The basic assumption is that nearly all economic, environmental, and societal impacts of a technology can directly be derived from the physical and technical properties of the involved technologies within the value chain. For that reason, the TDA includes the definition of the system boundary (Fig. 2) and the corresponding cut-off criteria, the definition of the functional unit (e.g. MJ of produced energy or Mg of used biomass) to be assessed, the modelling of a process flow chart for all phases of the conversion system and detailed mass and energy balancing for all phases of the value chain on scope. A good example for comprehensive mass and energy balancing can be found in literature [23].

Especially for biomass conversion systems, the upstream biomass cultivation and extraction looms large in the environmental, economic and societal assessment. The system boundaries of the TDA therefore include the agricultural processes or the processes related to biomass extraction, biomass transport and storage as well as the biomass conversion in a bio-refinery itself [24]. The use of cradle-to-gate approaches as standardized system boundaries is therefore recommended in the UAF. 'Gate' here means the exit gate of the bio-refinery. Depending on what kinds of products are assessed there could be two different definitions of the exit gates of relevance. When just energy carriers e.g. biogases, biocrudes, solids or platform chemicals are produced, the gate definition differs from a production process where end energy, chemicals or raw materials are provided. Fig. 2 depicts the difference between these two gate definitions. For the TDA an appropriate gate definition needs to be selected. However, in some cases the recommendation above might be too narrow (e.g. in the case of liquid and solid biofuels), so that in such a case the whole life cycle from cradle to grave needs to be evaluated.

Especially for new biomass conversion systems, for which data is scarce, it is required to produce custom data by lab experiments and thermodynamical calculation for a reliable execution of the TDA. For more matured technologies it is very likely that corresponding data can be found in the literature. In order to increase data comparability, especially between matured biomass domains and newly developing ones, two different approaches can be used. The first and less labor-intensive one is to use the structure of available data on existing biomass domains as a template for data production for newly developing ones. However, this approach limits future biomass system development and innovation. It should only be used when the system boundaries for both are well-aligned. The second approach is more labor-intensive, requiring the development of a common data structure for emerging as well as established biomass domains. While this implies that data sets for established biomass conversion systems need to be produced anew, it would allow for future system comparisons to be more accurate and reliable.

2.2. Life-cycle-sustainability-assessment – the impact level

The connection between the TDAs and the MCDM step is the triple bottom line assessment, implemented through a '*Life Cycle Sustainability Assessment*' (LCSA) sensu Klöpffer and Grahl [25]. It consists of a Life-Cycle-Costing (LCC), an environmental Life-Cycle-Assessment (LCA), and a Social-Life-Cycle-Assessment (SLCA) of the biomass conversion systems to be assessed (see Fig. 1). The first step within the LCSA is to select appropriate assessment criteria