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A participatory systems approach to modeling social, economic, and ecological components of bioenergy

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Abstract

Availability of and access to useful energy is a crucial factor for maintaining and improving human well-being. Looming scarcities and increasing awareness of environmental, economic, and social impacts of conventional sources of non-renewable energy have focused attention on renewable energy sources, including biomass.

The complex interactions of social, economic, and ecological factors among the bioenergy system components of feedstock supply, conversion technology, and energy allocation have been a major obstacle to the broader development of bioenergy systems. For widespread implementation of bioenergy to occur there is a need for an integrated approach to model the social, economic, and ecological interactions associated with bioenergy. Such models can serve as a planning and evaluation tool to help decide when, where, and how bioenergy systems can contribute to development.

One approach to integrated modeling is by assessing the sustainability of a bioenergy system. The evolving nature of sustainability can be described by an adaptive systems approach using general systems principles. Discussing these principles reveals that participation of stakeholders in all components of a bioenergy system is a crucial factor for sustainability.

Multi-criteria analysis (MCA) is an effective tool to implement this approach. This approach would enable decision-makers to evaluate bioenergy systems for sustainability in a participatory, transparent, timely, and informed manner.

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1. Bioenergy for human well-being

Human well-being depends on the availability of food, access to energy for cooking, shelter and heating, health care, and cultural components like political rights, education, communication, transport, and material comfort (Daily and Ehrlich, 1997). The availability of and access to many of these aspects can be traced back to access to energy in any form.

Maintaining and improving human well-being, in its various forms, is the moral foundation of most societies. The term "development", defined as "the process of change towards those future conditions desired by those targeted" (Leclerc, 2007), is the struggle of each society towards improved well-being. This process, whose components necessitate energy availability, is itself therefore highly dependent on societies' access to energy. Hall (2006) describes the importance of energy supply for wealth creation and sustained development, concluding that generation of wealth (in terms of products and services) has a close to one-to-one relationship with the use of energy per capita. The recognition of this relationship between energy and human well-being has led many to conclude that improving access to modern energy, like electricity, for the poor is a key component to achieve the United Nations Millennium Goals of halving poverty by 2015 (Department for International Development, 2002; Modi et al., 2006). A sustainable supply of energy, on the other hand, will necessarily influence development by keeping levels within the resources available and work as a tool to measure sustained growth.

Looming scarcities and associated social, economic, and ecological impacts associated with conventional sources of

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modern energy like fossil fuels or nuclear energy are again pushing the development of the renewable energy sources, namely biomass, hydro, wind, and geothermal. On a global scale, biomass use as a source of energy clearly dominates among the renewable energy sources. Solid biomass provides 45% of all primary renewable energy in member countries of the Organization for Economic Co-operation and Development, and over 90% of all energy needs of many Asian and African countries (Sims, 2003). Biomass is humanity's oldest non-food energy source; it requires minimal to no technology and is easily and widely obtainable.

Biomass sources vary broadly from fuelwood gathered randomly from forests and agricultural residues to dedicated energy crops like short-rotation coppice, manure, or industrial organic residues (e.g. wood, sugar, or food processing). Tapping into biomass to produce useful energy can be as simple as open fires using gathered fuelwood or as complex as "modern bioenergy chains" (Reijnders, 2006) encompassing advanced concepts from biomass feedstock production, supply chain logistics, and conversion technologies (e.g. combustion, gasification, fermentation, anaerobic digestion). End uses of biomass-derived energy (heat, shaft power, liquid or gaseous fuels, electricity) can range in scale from household applications to international distribution chains.

It can be expected that future development of bioenergy follows two principal directions: (i) an increase in bioenergy production in industrialized countries as part of the shift away from non-renewable energy sources and (ii) an increase in total bioenergy production in non-industrialized countries due to population growth and a change from traditional biomass use (e.g. cooking on open fire) to modern conversion technologies.

Bioenergy is complex because its three components—feedstock supply, conversion technology, and energy allocation—are influenced simultaneously by social, economic, and ecological factors. Understanding these factors, their interdependency, and their integration is essential, because failure of just one factor has led to the failure of many earlier attempts to introduce bioenergy systems delivering modern energy (Karekezi, 2001).

Most of the work on bioenergy systems to date has been on the various technical components to make them function. For instance, Volk et al. (2004) discussed several criteria related to sustainable short-rotation coppice production with willow. Lewandowski and Faaij (2006), Smeets et al. (2005), International Energy Agency (2006) and the Sustainable Bioenergy Wiki (2006) outline potential criteria and indicator sets to assess sustainability of bioenergy feedstock production and trade only. Heller et al. (2003, 2004) investigated the energy efficiency for bioenergy derived from short-rotation coppice by means of a life cycle analysis. Other authors discussed overall sustainability criteria for bioenergy systems (Reijnders, 2006), van den Broek et al. (2000, 2002) assessed socio-economic factors of bioenergy and non-bioenergy alternatives in different countries based on cost-effectiveness and jobs created.

While these efforts are crucial to success, there are broader considerations which are also essential to success and which have not received much attention: namely, approaches enabling decision-makers to choose when, how, and where to deploy bioenergy systems for sustainable development. Considering all the components of the system—feedstock production, conversion technology, and energy allocation—while paying attention to social, economic, and ecological factors is crucial for assessing different bioenergy systems or comparing bioenergy with other energy sources. This always requires involving people other than technical experts. However, integrated methods serving as an analytical tool by modeling bioenergy systems encompassing all components, factors, and interactions while allowing for participation are lacking. This methodological gap is one of the bottlenecks for broad replication of bioenergy systems (Food and Agriculture Organization, 2006; Lettens et al., 2003) resulting in high project preparation costs and time (White, 2002) and making replication of successful projects difficult.

For a wide implementation of bioenergy systems, we need to create methods to model the components and factors of bioenergy systems and their interactions, which in turn allow us to make decisions that contribute to development. In other words, we need an integrated approach to model the social and economic impacts of bioenergy for planning and evaluation purposes, to check whether a bioenergy system can fulfill our social and economic goals (Domac et al., 2005). By compiling criteria sets, the first steps towards such a tool have been taken but a holistic concept is still missing. In order to make a tool that is universally acceptable, we must ask the following questions: How can we generalize the obstacles experienced by bioenergy implementations? How can we predict the impact of bioenergy implementation on society?

2. Considering all factors—sustainabilty

We suggest that an adaptive systems approach to assess the sustainability of a bioenergy system provides a solid basis for such integration. Assessing sustainability not only integrates social, economic, and ecological values, but it also provides useful information for decision-making through participation. Such a participatory systems approach would enable decision-makers to evaluate bioenergy systems for sustainability in a transparent, timely, and informed manner. We propose that multi-criteria analysis (MCA) is an appropriate decision support tool towards these ends.

Sustainability is a dynamic, indefinite, and contested concept (Costanza and Patten, 1995; Mog, 2004). Holling (2001) defined sustainability as "the capacity to create, test, and maintain adaptive capability", meaning that systems are sustainable when they possess now and in future the necessary infrastructure and material wealth to make adaptations. This definition implies that it is process-oriented rather than goal-oriented and in a social context it encompasses many human values, perceptions, and political interests. Sustainability as a social value requires the consideration of broader economic and social values. Therefore, it is by nature controversial. For instance, some place the social, economic, and ecological factors of sustainability on the same level while others support the view of a nested sustainability, stressing that sustainability can only be achieved when its social and economic factors do not violate ecological limits (the biophysical view of sustainability, Gowdy, 1999).

The multiple perspectives encompassed in the concept of sustainability furthermore are subject to frequent changes and scientific uncertainties. For instance, how many future generations does sustainability consider (temporal scale)? Is sustainability locally achievable or only on a global level (spatial scale)? How can future benefits be compared with current ones if they differ in type (Bruntland, 1987)? In other words, sustainability is a diverse and evolving concept. Therefore, making sustainability a concept that is operational—in this case, for bioenergy systems—is a challenge that requires an adaptive and integrated approach.

To date, sustainability efforts have been based on the well-known social–economic–ecological three-legged stool, which has moved us well in the direction of considering the many factors of a system. However, efforts to assess sustainability based on the social–economic–ecological concept are still somewhat ad hoc in their approach to come up with the criteria we need in each of the three factors. The social–economic–ecological concept does not give us the analytical capability to determine whether an influencing factor has been left out or has been over-specified, thereby limiting our ability to interpret the outcomes of such sustainability assessments (Rockwell, personal communication, 2006). Therefore, this ad hoc approach leaves many questions open in terms of which factors are chosen or left out, who is to choose them, how trade-offs are addressed, and how they influence decisions concerning sustainability.

One of the most advanced, accepted, and practised approaches to assessing sustainability today is the Forest Stewardship Council (2006). A universal set of 10 principles (or criteria in the highest hierarchy) which can be associated with social, economic, and ecological factors is applied to all assessments for sustainable forest management. While in the early stages of the FSC approach rather intuitive applications of this criteria and indicator approach were common, Wolfslehner et al. (2005) has since observed a shift to more science-based applications. But how can we integrate all such factors with scientific tools? How can we improve the predictive power of sustainability assessments if we do not know what the expectations to an evolving bioenergy system will be in an uncertain future and if we do not have the confidence that the complex system has been fully specified?

3. Adaptive systems approach to model impacts of bioenergy systems

3.1. Introduction to adaptive systems analysis and when to use it

In the following, we show that a systems approach, and adaptive systems in particular, offers several insights when approaching a holistic and evolving concept like sustainability. This is especially true when applied to rapidly evolving and integrated systems like biomass production, conversion, and use. Farley et al. (2005) considers a systems approach or systems analysis as especially valuable when problems are complex and urgent, and stakes are high. A systems approach stands in contrast to the reductionist approach in science, in which systems are broken into parts to study and understand them in isolation. Its methodology is based on (i) the idea that "the whole is greater than the sum of its parts" (Aristotle) and (ii) that there are general system principles that characterize any existing system (von Bertalanffy, 1968). Therefore, a systems approach using these general principles specifies all factors and interactions within a system in a directed, comprehensive way. System approaches have long been used by scientists from such different fields as ecosystems modeling, economics, and psychology.

3.2. Bioenergy as an adaptive system

To describe the systems approach more in detail, we give an example of a bioenergy system and briefly explain the underlying general principles of systems. The objective here is to outline why it makes sense to model sustainability through an adaptive systems approach.

We introduce the adaptive systems approach by analyzing a bioenergy system on the basis of a very simplified diagram of a bioenergy system as seen in Fig. 1. Diagrams allow one to view a system through a "macroscope", as Odum (1971) puts it. For the purpose of systems analysis, the term "model" here can also be understood in a broader sense. Making models means to simplify the system or reduce its complexity to a degree overseeable for the human brain. Modeling and diagraming help elucidate basic principles and organizational structure and reveals that the complex and often confusing interactions in a system can be generalized by a few general principles. Actively influencing or passively monitoring these principles can reveal a lot about complex systems. As Holling (2001) puts it, "there is a requisite level of simplicity behind the complexity that can lead to an understanding [...], complexity emerges from a small number of controlling processes". And he further states that "if you require more than a handful of causes, then your understanding is too complex". Consequently, a systems approach allows the simplification of complex systems by identifying and concentrating on certain common principles without losing a holistic overview of systems; the principles identified

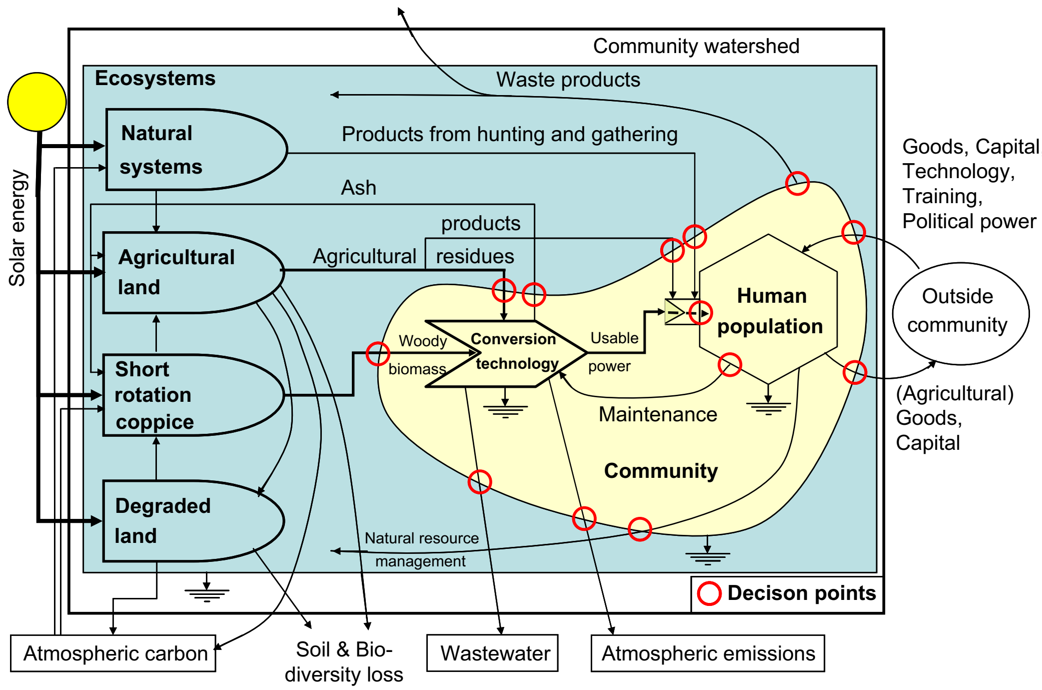

Fig. 1. System diagram for short-rotation coppice-based subsistence bioenergy in a rural community.

focus on interactions among components, change over time, novelty, and uncertainty.

By using the general systems principles, we can more fully and effectively capture the components and interactions of a bioenergy system and hence model its sustainability in a superior way than the social–economic–ecological three-legged stool approach allows. Connecting the bioenergy system example with general systems principles reveals why a system may be prone to failure or why problems arise.

Fig. 1 diagrams an imaginary bioenergy system within a watershed boundary of a rural community. The biomass feedstock is primarily derived from short-rotation coppice and agricultural residues, the technology applied is a small-scale gasification system, and the usable energy might be shaft power, electricity, and heat delivered to the local community. Shapes symbolize subsystems and components, and feedback loops interconnecting the subsystems can be diagramed as arrows. The symbols and modeling process is based on the Energy Systems Language developed by Odum for circuit diagrams. For an in-depth description of the symbols used, see Odum (1996).

In Fig. 1, energy flows in from the sun into four ecosystems: ‘‘natural system’’, ‘‘agricultural system’’, ‘‘short-rotation coppice’’, and ‘‘degraded lands’’, which are symbolized by bullets. For agriculture, land was cleared from natural systems, which is symbolized by an arrow going from ‘‘natural systems’’ to ‘‘agricultural land’’. ‘‘Agricultural land’’ became degraded and therefore is linked with the bullet symbol of ‘‘degraded land’’. In this example, the idea is that ‘‘short-rotation coppice’’ systems will be established on degraded lands and eventually—after site restoration takes place—will be rendered ‘‘agricultural land’’. These interactions are symbolized by the arrows linking the different production systems. Diagraming the boundary of the system and its cross-boundary interactions reveals that the community is nested within a respective next larger (eco)system. This is a general pattern in systems called hierarchical emergence. A system is an organized set of components that in turn are composed of a series of smaller sets of components (or subsystems), which themselves form part of a larger set (or supersystem, Hammond, 2003). Emergence refers to the fact that each level has properties that cannot be explained solely by referring to the properties of its components. At the same time, a component cannot be fully understood without studying at least the next upper and lower hierarchical level in which it is nested. Through hierarchical control, each level promotes or constrains the actions of the level below.

Systems can be dynamic or adaptive. Dynamic systems have the ability of self-control or self-correction: within its boundary, a system must have an adequate degree of control or it will not survive. The ‘‘natural resource management’’ arrow in Fig. 1 symbolizes the options the community possesses to give a feedback to the ecosystems productivity, i.e. to control it and steer it in a desired direction. This control makes a system resilient to a certain extent within its fairly closed boundaries to internal and external impacts. Control is hierarchical, and excessive control can limit a system’s ability to adapt to new conditions (see, for instance, the inefficiency of central planning, Oliver and Twery, 1999); insufficient control, on the other hand, reduces a system’s ability to determine outcomes in normal conditions. Dynamic systems employ a mechanistic paradigm and strive for stability and equilibrium, as in the case of cybernetics (Hammond, 2003). Dynamic systems seek to encapsulate their interactions with their environments, obtaining predictable reactions for set inputs.

Control is derived through means of communication. Communication or information transmission allows the access and transfer of information for regulation, and functions principally through feedback loops as described above. Feedback loops can be negative or positive. Negative feedback loops are of special importance for dynamic systems. A negative feedback loop restrains a certain structural development in order to approach equilibrium (steady state, balance); consequently, it tends to be goal-oriented and conserve conditions.

It becomes clear that the bioenergy system is not well described by a dynamic system, striving for control and stability. In this bioenergy example, too many factors are constantly changing and beyond control: inflow of new ideas or information, new conversion technologies, climate change, etc. In order to thrive in changing environments, some systems learn, create, and grow. Such systems are called adaptive systems. Adaptive (also known as evolving) systems not only have all the abilities of dynamic systems but also have properties that go beyond self-control. They are perceived as having self-design or self-organization (Odum, 1971, 1988). In contrast to dynamic systems, agents within adaptive systems interact, react, learn, and coevolve with their environment. Because of the ability to design its own shape, bioenergy systems are better described as adaptive systems than dynamic systems. For example, the ‘‘natural resource management’’ arrow in Fig. 1 symbolizes the options the community possesses to give a feedback to the ecosystem's productivity, i.e. to steer it in a desired direction.

Under such changing conditions, information storage and communication gains a completely new dimension: adaptive systems need a widely accessible storage of information or diversity to allow for the generation of new alternatives. With respect to the sustainability of societies, effective communication requires access to as much information as possible, i.e. an effective means of information storage (Odum, 1988), and consideration for many human values, perceptions, and political interests. In more general terms, von Bertalanffy (1968) stresses the creativity and spontaneity of adaptive systems as a means of changing over time to maintain resilience (Hammond, 2003). To identify and constantly adapt best management practices for natural resources in such a complex (bioenergy) system, participatory approaches allow us to tap into vast information pools by including especially local expert knowledge in particular. Mog (2004) therefore emphasizes the need for participation of local stakeholders in order to tap their perceptions and knowledge when pursuing sustainability.

As an example, the community in the bioenergy example in Fig. 1 maintains the power plant and produces (agricultural) goods for its own consumption and trading. It receives training, funding, and technology from outside communities to run the power plant. This initial information dependency of the community to outside communities in terms of training and knowledge is often necessary when transferring high-tech solutions to developing countries and is rarely taken into account for sustainability assessments. Long-term influx of funds, technology, and knowledge signals a dependency on outer energy resources and hints at unsustainable performance on a local level. Participation can be a key to identify such information flows and fostering learning processes among both outside and local experts. The failure to listen and to address concerns expressed by stakeholders has often resulted in the failure of bioenergy systems (Banerjee, 2006; Upreti and van der Horst, 2004; Upreti, 2004). Participation can greatly help in adapting bioenergy designs to new environments.

The constant movement among several optima and varying social values in adaptive systems implies that there is no single optimal state or Pareto optima, trade-offs always have to be made. Adaptive systems evolve over time, making them more difficult to predict. The outcome of evolution is unpredictable; there are several paths to several optima. Therefore, uncertainty or a lack of information is in the very nature of adaptive systems (Holling, 1978). From an ecological perspective, energy systems based on biomass, when poorly planned and managed, risk accelerating environmental degradation by feeding on unsustainable biomass sources (soil loss, over-exploitation of agricultural residues). Therefore, poorly managed feedstock supply can result in environmental damage even in the face of efficient conversion and allocation. Although some studies expect hard choices in allocating land to satisfy human needs in the near future (Hall, 2000; Reijnders, 2006; Sims, 2003) with the potential for food and energy crops competing for acrage, Hoogwijk et al. (2005) predict favorable conditions for bioenergy production on a global scale and especially in sub-Saharan Africa. Models from the Food and Agriculture Organization (Bruinsma, 2003) assume global food security for the next decades, and Perlack et al. (2005) believe that a future sustainable national supply greater than one billion tons of biomass per year is possible for the US.

Despite its potential, the uncertainties and risks associated with bioenergy systems often create a bias to proven energy systems like fossil-fuel-based technology or technology-based renewable energy sources, namely hydro, wind, or solar panels. Unlike risk, uncertainty refers to events where we cannot specify probabilities (Millet and Wedley, 2002). To approach uncertainty, one has to understand ‘‘what is known and what is not known’’ (Reynolds et al., 1999) and even what is not known to be not known (ignorance, Faber et al., 1996). To operationalize uncertainty and risk, i.e. putting values on them, is inherently subjective and therefore justifies a participative process involving concerned stakeholders. Holling (2001) describes the uncertainty of assessing sustainability of adaptive systems as resulting from the fact that ''the system itself is a moving target''. To manage uncertainty, Ludwig et al. (1993) suggest to (i) use a variety of strategies and hypotheses, (ii) hedge, (iii) apply informative and reversible actions, (iv) monitor, (v) assess, and (vi) modify policy. Based on these insights, Holling (1978) therefore introduced modeling to ecosystems management, using the term ''adaptive management'' for constantly monitoring results, re-evaluating decisions, and learning on the strife to sustainable ecosystem management. The diagram in Fig. 1 shows how unique and fine-tuned every setting of a bioenergy system can be. This implies that there are rarely standard solutions for different locations in terms of technology, nor are there standard trade-offs between negative impacts on ecological systems and the economic profit of the bioenergy system. As already stressed when discussing creation of alternatives, it makes sense to have several optima or multiple equilibria (Costanza, 1996), for example, in terms of different technologies existing next to each other, also to enhance evolution of new approaches.

Another source of uncertainty is the irregular production cycle of bioenergy systems and adaptive systems in general: systems are subject to pulses (Odum, 1988). Implications of pulsing are the impossibility of assuming steady growth or balanced biomass production from the ecosystems as well as consumption patterns for usable energy. Negative feedback loops can lead to oscillation or pulsing even in dynamic systems by (i) long time lapses between causes and feedback loops regulating the system and (ii) forceful responses provoked (Holling, 2001). Pulses can also be caused by positive feedback loops which strongly influence adaptive systems. Positive feedback loops enforce structural developments that increase the power of the structure, leading in an autocatalytic process more to an evolving and open future development. Positive feedback loops can create powerful growth patterns until hitting a point where the system collapses. Such patterns can occur frequently and the subsequent pulses are often perceived as very strong (Odum, 1988). Such growth eventually allows for selection of superior alternatives through competition. An implication from pulsing for bioenergy systems might be an approach of scaling up bioenergy systems in small steps and units, which might more effectively react to pulses than building large-scale units relying on projections of steady growth (Lovins, 2002).

All the general system principles discussed are scale-independent (Brown et al., 2004). However, with increasing spatial scale, techniques have to be adapted to reduce associated uncertainties and risks of failure; ''the bigger the project, the better the techniques [have to be] to respond to anticipated impact growing with scale'' (Pétry, 1990). Scale matters. From a society's point of view, small-scale projects allow more experimentation due to lower associated impacts in case of failure. The same is true when it comes to increasing bioenergy's share of the present human energy supply: problems experienced now with lower shares of bioenergy are likely to worsen with increasing production. This implies that for small-scale bioenergy systems higher risks could be accepted in assessing its sustainability than for large-scale projects (for scale or boundary-related sustainability considerations, see also Norgaard, 1994). Another important aspect is increasing longevity of systems with increasing scale. A small system can fulfill its purpose, i.e. be sustainable, in smaller time scales than larger systems in which it might be nested (Costanza and Patten, 1995; Holling, 2001; Odum, 1988).

Moreover, the diagram highlights the crucial role of energy flows and balances in the system, i.e. the ratio of how much energy (natural, financial, human, and social capital) the community has to invest into the bioenergy system compared with how much useful energy is produced. Maximizing available energy is a central determinant of any system's behavior. Odum (1988) describes the importance of energy flows, the laws of thermodynamics, and the quest for maximum power, i.e. the trade-off between efficiency and power output, as the primary driver for systems in general (see also Cai et al., 2004). He drew particular implications for the future of human society under fluctuating energy availability (Odum, 1971; Odum and Odum, 2001). The contribution of bioenergy sources to energy flows within larger societal systems are therefore of outstanding relevance for sustainability assessments.

Energy supply by itself does not guarantee communities' and societies' human development since many of its benefits tend to accrue in wealthier groups (Karekezi, 2001; World Energy Council, 1999). Such a social phenomenon has to be considered in sustainability assessments of bioenergy systems. In general systems, this is known as ''lock in'': positive feedback loops can conserve conditions with increasing strength through increasing return, leading eventually to a survival of the first rather than survival of the fittest (Costanza, 1996). In the case of a bioenergy system, this could mean that securing their own energy supply through establishing a bioenergy system might lead a wealthier group to a ''lock in'' phenomenon, allocating energy for leisure purposes, when distribution could have a greater impact on development elsewhere. In this ''lock in'' example, the wealthier class self-sustains and strengthens its position of control through improved access to energy without contributing to a broader development goal. A broader development goal, in contrast, could be accomplished by directing energy to natural resource management improvement through augmented education and labor, which eventually increases biomass availability for power production—a positive feedback loop of development. To check for such energy allocation issues, one would need to diagram the interactions within the community in more depth. It is essential to track who carries the burdens (e.g. labor in power production, decision point ''maintenance'') and who reaps the benefits of improved energy services (e.g. who gets shaft power, electricity, or heat). Such issues can be tracked by focusing on the decision points in Fig. 1. For example, the feedback loop ''natural resource management'' could be linked to one social class (which is actually doing the job) but analysis might reveal that the energy inflow does not benefit this class.

4. Implementing a systems approach in decision-making

4.1. Decision-making in complex environments

As mentioned earlier, sustainability is an open, evolving concept subject to many individual interpretations and values. On the quest to operationalize sustainability, we therefore encounter several challenges: the evolving nature of sustainability makes it hard to predict, the integrated nature behind it makes it hard to understand the system, and the many human values associated with sustainability make it hard to decide. Joyce (2003) puts it this way: ''the challenge is to do planning and decision making while balancing three tensions: (1) maintaining scientific credibility, (2) assuring practical saliency, and (3) legitimizing the process to multiple participants''.

As laid out in the previous section, general systems principles offer a high scientific credibility and strong analytic capability when assessing sustainability of bioenergy systems. General systems principles allow the modeling an existing system's viability or construction of a system that is functional. For a broad support of bioenergy system development, the next challenge lies in identifying a time-efficient formal approach that not only applies general systems principles but is also capable of incorporating information from as many experts and non-experts as possible while keeping the decision process transparent to third parties. To bridge this gap is a crucial task. Discussing sustainability from a scientific perspective, Levin (1993) stressed that ''…we must not delude ourselves into believing that the issues are entirely scientific […]. What is needed are mechanisms for performing science that will guide society in making decisions and for building bridges between science and decision making''.

Formal or standardized approaches to decision-making—also called decision support tools—address the complex array of interactions in systems by structuring the collection and evaluation of quantitative and qualitative information about a system and identifying a system's leverage points. Decision support is the process of framing information as effectively as possible so that the decision-maker will base the decision on the best possible knowledge of the outcomes (Oliver and Twery, 1999). Its goal is to reduce uncertainty and make the outcomes and consequences of a given decision more predictable, or at least help in the detection of possible consequences (i.e. reduce ignorance). While doing so, the goal of the decision-making approach must be to amplify the power of decision-makers without usurping their right to use human judgment and make choices (Pétry, 1990; Rauscher, 1999).

To that end, a modeling approach that analyzes sustainability of bioenergy systems by applying general systems principles has a high analytic power. In order to assure its applicability, this approach also needs (i) to allow decision-makers to identify and evaluate risks in ever-changing environments based on their risk perception, (ii) integrate their own values, and (iii) gather as much information as possible encompassing all stakeholders, components, and interactions of the bioenergy system. These capabilities have to be core characteristics of a participatory systems approach applicable for adaptive systems like bioenergy. MCA is a decision support tool that can meet these conditions and is discussed in the following section.

4.2. Modeling bioenergy systems with MCA

4.2.1. Introduction to MCA

MCA offers a formal approach to decision-making. MCA uses criteria that allow decision-makers to structure, model, and analyze problems and various outcomes depending on feedback loops, weights, and values associated with the criteria, all while incorporating many stakeholders. One of the greatest advantages of MCA is its ability to include qualitative information and restrain from unifying units (Gowdy and Erickson, 2005). Subsequently, MCA is able to include social issues that most other decision approaches like life cycle analysis or operations research miss. The use of MCA can follow a general path: (1) define problem, (2) specify a set of evaluation criteria, (3) generate alternatives, (4) evaluate dominance of alternatives, (5) apply criterion weights, (6) rank alternatives, and (7) execute a sensitivity analysis (Farley et al., 2005). The analytic hierarchy process (AHP) and the closely related analytic network process (ANP) are two of the most widely used and best structured MCA approaches. Both processes, originally developed by Saaty (1977, 1980), use a ''ratio scale theory'' based on a pairwise comparison of criteria and a subsequent ratio scale estimation for each criteria, usually employing a nine-point scale. Before comparing criteria based on their perceived importance, the ANP allows for inclusion of feedback loops to determine an indicator's rank and weight (Saaty, 1996). For a more in-depth analysis of MCA, Belton and Stewart (2002) and Mendoza and Martins (2006) discuss different approaches and techniques of MCA in general and applications for natural resource management in particular, respectively.

4.2.2. Criteria and leverage points

The idea behind MCA is to simplify complex systems by using a restricted number of criteria and structuring them in a way that clarifies relationships, impacts, and outcomes. A vast collection of criteria for modeling and assessing sustainability of bioenergy systems—however important they might be—does not improve the model significantly. The key for modeling bioenergy systems lies in identifying those ''handful of causes'' (Holling, 2001) that can explain the system satisfactorily and can be used to shift the system to make it more sustainable. Identifying these causes means to identify leverage points, with which one can best model, influence, and monitor systems. Going back to the bioenergy example in Fig. 1, every interaction of the community within itself and with its environment depends on decisions. The red circles in Fig. 1 identify the decision or leverage points, i.e. those points where decisions can most effectively influence the performance of the bioenergy system. Meadows introduced leverage points as a unifying concept of systems, describing them as ''those places in a system where a small shift can lead to large changes in everything else'' (Meadows et al., 1972). When leverage points are identified, assumptions about the current state and future development of the system can easily be made with a restricted amount of data and knowledge. MCA can be a useful tool to identify these leverage points.

4.2.3. Advantages of MCA

In the following, we restrict our discussion on MCA to some core aspects that make it valuable for modeling and analyzing bioenergy systems as adaptive systems, including social and economic values. By referring to the bioenergy example, we outline how MCA can integrate general systems principles into a decision-making framework.

In dynamic systems like mechanistics or cybernetics, it suffices to examine differences in output based on inputs, searching for threshold values that indicate system change or collapse. This process is goal-oriented. One of the largest problems, however, even in dynamic systems is to identify those thresholds values under the premise of pulses and therefore give often questionable reassurances. In contrast to dynamic systems where leverage points can be identified by focusing on goals, thresholds, and equilibrium, identification of leverage points in adaptive systems like in the bioenergy example in Fig. 1 has to focus on those points which, when manipulated, cause changes in structure and process. Thus, the leverage points in adaptive systems can be considered to be process- or structure-oriented (Wolfslehner et al., 2005). Mog (2004) suggests more process indicators for criteria and indicator approaches like ''people involved'', or ''use of local knowledge''. MCA tools are particularly valuable in situations where criteria are especially hard to measure, i.e. limited or dissimilar information is available and a systematic derivation of informed decisions requires many participants with different expertise and interests (Mendoza and Prabhu, 2005)—as it is often the case in decisions on bioenergy systems. Assisting broad participation, an MCA approach maximizes communication and taps into information storages, especially by integrating the knowledge of local people. For instance, MCA can help decision-makers realize what is feasible (e.g. maximize environmental benefits) at what associated costs or sacrifices (e.g. increased power costs). Being aware of the trade-offs is the essence of informed decisions. The iterative process of MCA, adapted and controlled by stakeholders, allows for learning processes to take place and can integrate new information into the decision process. Considering different perspectives that come with different scales, MCA also accommodates hierarchical emergence within systems. Applying an MCA for modeling a bioenergy system can therefore deal with bioenergy systems on scales ranging from local (e.g. small-scale power plants) to national or international (e.g. bioenergy policies).

An additional strength of MCA is that it handles evolving processes within systems, encompassing the possibility of several optima (Pétry, 1990). Most other decision tools make a priori goals and decisions on an extremely detailed level rather than allowing a continual, responsive decision-making process (Reynolds et al., 1999). For example, operations research based on linear programming terminates with a single optimal solution such as cost-effectiveness, with no feedbacks typical for adaptive systems.

There are multiple methods to measure risk through MCA (Millet and Wedley, 2002), and broad stakeholder participation further reduces uncertainty. For example, the individual weighting of criteria and several options allowing for sensitivity analysis are ways MCA deals with uncertainty.

4.2.4. MCA as a decision framework

It becomes clear that ''models do not provide solutions but are methods to understand and learn more about the system being modelled'' (Mendoza and Prabhu, 2003). The emphasis of MCA techniques is in structuring the problem, i.e. building a model by selection of important criteria and connecting them, and only secondarily in facilitating an informed decision (Mendoza and Martins, 2006).

Criteria and indicator approaches are widely applied for sustainability assessments of environmental management systems today like the Forest Stewardship Council (FCS, 2006) or the ISO 14001 certificate (International Organization for Standardization, 2006). In a criteria and indicator assessment, a system is evaluated against a given set of criteria. However, most of the criteria in the representative FSC approach are goal-oriented and performance-based with threshold values (more scientific) or yes/no answers (more intuitive and/or qualitative) and are tested independently. Due to this goal-oriented process, the criteria and indicator approach can be criticized as loose and static (Mendoza and Prabhu, 2005) with little influence of process-oriented indicators describing feedbacks in the system and impacts of the indicators on each other. Moreover, these approaches tend to be less transparent because they are based on many intuitive decisions by experts, which are neither transparent nor participatory. These criticisms do not prove valid for MCA.

For instance, Mendoza and Prabhu (2000, 2003, 2005) describe how an MCA approach can give more structural and methodological rigor to a criteria and indicator approach, making it more stochastic and predictive while its simple and intuitive structure is still transparent and suitable for broad participation. Reynolds et al. (1999) also suggested such a combined method; using the AHP, as a pre-processor for indicator identification and using more quantitative tools in a second step to verify indicators.

Therefore, in order to facilitate the implementation of sustainable bioenergy systems, we suggest that an approach based on criteria and indicator sets must be extended to an adaptive, self-renewing process through a systems approach with broad and ongoing participation by means of MCA. In other words, a criteria and indicator approach is a technical tool that needs to be nested within a decision structure like that offered by MCA. The application of this tool would be independent of the scale of the bioenergy system envisaged. The novelty of this concept is that it goes a step further than previous approaches. It could (i) apply existing criteria and indicator sets for assessments of alternatives and (ii) be nested in an existing MCA technique that not only assists in participatory systems modeling (criteria ranking and alternatives discussion, Mendoza and Prabhu, 2005) but also supports informed decisions and evaluation of bioenergy systems.

Lists of criteria already exist (Lewandowski and Faaij, 2006; Smeets et al., 2005; International Energy Agency, 2006; Sustainable Bioenergy Wiki, 2006) for sustainability assessments of biomass production systems. However, to date, these ad hoc criteria sets are untested, not structured to rank the importance of factors, fail to integrate the interaction of factors, are not designed for application of various scales, and would need to be extended in scope to include the whole bioenergy system. To allow maximum detection of the structural components of a bioenergy system, these criteria have to be sorted to (i) identify those that are structure-oriented ones and (ii) see which parts of the general systems principles are poorly addressed and need extension. Participative MCA applications can contribute to this task.

Investigating other formal approaches to decision-making like life cycle analysis, operations research, or simulation modeling reveals that MCA does not compete with them but, rather, that they complement each other. These other approaches contribute to better understanding and verification on the criteria level of MCA (Kangas and Kangas, 2005; Millet and Wedley, 2002), while the MCA itself gives structure, inclusion of social and economic factors, feedback, and options for participation.

5. Conclusion

In this paper, we outline where the problems lie for wide implementation of bioenergy systems and suggest a methodology for approaching its complexity. To assess whether a bioenergy system can fulfill expectations, we need an integrated approach to model social, economic, and ecological impacts of bioenergy. In other words, we need a planning and evaluation tool helping us to decide when, where, and how bioenergy systems can contribute to development. By compiling criteria sets, the first steps towards such a tool have been taken, but a holistic concept is still missing.

We argue that one way to do such an integrated modeling is by assessing the sustainability of a bioenergy system. Assessing sustainability not only provides integration but also taps useful information for decision-making through participation. We further imply that the evolving nature of sustainability can be described by adaptive systems. Based on general systems principles, sustainability of bioenergy systems can be assessed with a high analytical power by identifying a few leverage points of great influence. General systems principles also imply a high involvement of stakeholders.

Participatory approaches to gathering data and making decisions allow us to meet multiple goals. While obtaining good data, such approaches effectively engage people in the decision process. A participatory systems approach brings together sustainability assessments with general system principles through a strong emphasis on participation. An effective tool to apply general systems principles to model sustainability of bioenergy systems is multi-criteria analysis (MCA).

MCA can be a quantitative and predictive approach that allows simple comparisons between alternatives or different trade-offs. It allows broad participation through transparency, with a clear and simple structure. It also offers approaches for dealing with uncertainty and risk, deals easily with qualitative data, and has the means to value process-oriented criteria.

Such an organizing framework involves non-technical people in feasibility research and ultimately in decision-making. It enables decision-makers to evaluate bioenergy systems for sustainability in a participatory, transparent, timely, and informed manner that includes social and economic considerations and is less input-intensive (quantitative data requiring) than other commonly used approaches (such as life cycle analysis) while giving results comparable in accuracy. Such a tool would greatly improve the chances of successfully implementing a bioenergy system.

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