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Considerations of Project Scale and Sustainability of Modern Bioenergy Systems in Uganda

THOMAS BUCHHOLZ and TIMOTHY A. VOLK
State University of New York, College of Environmental Sciences and Forestry, Department of Forest and Natural Resources Management, Syracuse, New York, USA

Energy supply and accessibility has a major impact on the development of societies. Modern bioenergy production in the form of heat, electricity, and liquid transportation fuels is increasingly cost competitive as prices of fossil fuels continue to increase. However, the large potential benefits associated with bioenergy come with a price tag and risks that may be disproportionately carried by tropical and non-industrialized countries. This analysis focuses on the influence of project scale on economic, social, and environmental impacts of bioenergy production in the tropics using the framework of two wood fueled bioenergy projects in Uganda—a large (50 MW) and a small-scale (200 kW). There are indications that less sustainable practices often come with increasing project-scale. This study found that a distributed, small-scale infrastructure indeed can be more desirable in terms of resource efficiency, impacts on ecosystems and local societies, and financial risks and benefits compared with those associated with one large-scale. To support the implementation of small-scale projects, there is a need for policies fostering distributed energy infrastructure and participatory tools beyond traditional cost-benefit analysis to assess sustainability of bioenergy systems.

KEYWORDS *bioenergy, distributed energy production, forestry, project scale, Sub-Saharan Africa, sustainability*

Address correspondence to Thomas Buchholz, University of Vermont, Gund Institute for Ecological Economics, 617 Main street, Burlington, VT 05405, USA. E-mail: thomas.buchholz@uvm.edu

BIOENERGY IN A GLOBAL CONTEXT

Availability of and access to energy sources is one of the main drivers of development for societies. Modern bioenergy systems, such as electricity produced from woodchips, is increasingly attracting attention for its potential to fill the gap between dwindling fossil fuel reserves and increasing global demand for energy. Indeed, the absolute quantity of biomass contributing to human energy needs increased by 80% in the last three decades, mainly in non-OECD (Organisation for Economic Co-operation and Development) countries, while its overall contribution to the global energy portfolio stagnated at around 20% during the same period (Sagar & Kartha, 2007). The human appropriation of the biological net primary productivity (NPP) of the planet is estimated to be as high as 39% (Haberl & Geissler, 2000), but the total NPP is declining due to human influence (Haberl, 2002). As the use of biomass increases to meet the growing demands for livestock feed (which consumes 30–75% of all biomass harvested by humans; Krausmann, Erb, Gingrich, Lauka, & Haberl, 2008), fiber, food, and energy, the impact on ecosystems and their NPP levels will need to monitored to ensure that these NPP levels do not continue to decline.

Bioenergy production has a potential to improve human well-being by delivering energy on a long-term sustainable basis more efficiently than other sources of energy (e.g., Banerjee, 2006 for India). However, the large potential of bioenergy with its array of potential benefits can also have negative impacts if not implemented properly. Some bioenergy projects create problems such as competition with food production, disruption of social cohesion in local communities by focusing on production of products for export, and negative impacts on biodiversity and productivity of pristine and fragile tropical forest ecosystems (Hall, 2000; Sims, 2003; Reijnders, 2006), and potentially additional disruptions in the carbon cycle through indirect land use changes associated with the expansion of bioenergy systems. A number of these issues illustrate the interdependency of social systems and ecological systems (e.g., Searchinger et al., 2008). The challenge is to design sustainable bioenergy systems so that the social and economic benefits can be maximized while maintaining the protective and productive functions of the ecological and social systems on which the bioenergy system is dependent.

Is There a Tendency to Large-Scale Bioenergy Projects?

As interest in bioenergy increases, so does a focus on projects based on the “economy of scale” principle. For instance, a 750 MW coal power plant in Tilbury, UK, has been temporarily converted to be fueled by 100% wood (The Guardian, 2011); while to date, installed biopower systems range from a few kW to below 100 MW per plant (e.g., Wiltsee, 2000 for systems

>10 MW). A focus on large-scale solutions developed in and for temperate industrialized countries has often been promoted as an equally viable solution for tropical developing countries. Drivers for using and developing large-scale systems include the familiarity of these systems to international investment firms, technology developers, and project managers. As a result, large-scale systems tend to have access to a greater pool of information and capital to be developed and launched. In contrast, Austria has long pursued a policy of small-scale, distributed biomass power systems which has resulted in the installation of 113 small-scale (<5 MW) power plants across the nation fueled by solid biomass with an installed capacity of 312 MW for all plants by 2008 (OeMAG, 2009). A question that remains is whether large- and small-scale systems contribute equally to societies' overall goals of sustainable development and exert the same stress on the surrounding ecosystems and communities.

In traditional economic analysis (e.g., cost-benefit analysis), factors that can be monetized receive the most attention while less quantifiable social or environmental impacts or benefits are either unaccounted for or included using methods that are still not refined. The emphasis is often on indicators such as internal rate of return or total direct jobs created, which are more easily quantified and under which large-scale projects often perform better than small-scale projects. In addition, large-scale projects are often easier to promote to both public authorities and project managers for a number of reasons. They are easier to control (in terms of environmental impacts, job regulations, etc.) as single point source projects. Also, they are more likely to attract tax breaks in direct negotiations with the government. Large-scale projects have easier access to carbon markets and can produce more visible side benefits (e.g., specific community development projects). And finally, they are more likely to attract attention from the media.

The goal of this article is to explore how current approaches to assess economic, ecological, and/or social sustainability can influence the choice between small- and large-scale bioenergy projects that will ultimately have the same energy output. In particular, we want to show how a systems approach can broaden the depth of such assessments.

Comparing Large- with Small-Scale

There is no generally agreed methodology to compare large-scale bioenergy systems with those of small-scale, and practical examples dealing with the sustainability of bioenergy systems in relation to the project scale are limited. Burton and Hubacek (2007) suggest that small-scale renewable energy projects offer most value in ecological and social terms (local trade, job creation, etc.) compared to large-scale projects, while large-scale projects fare better in economic terms measured with cost-benefit analysis in their study. However, in their study, the impacts on the social and ecological impacts of these large-scale projects were measured on purely normative scales. Bird (2007) proposes the use of different sets of criteria for bioenergy systems at different spatial scales. Transport distances (e.g., Bernesson, Nilsson, & Hansson, 2006) and supply logistics (Maker, personal communication, December 27, 2007) seem to have an increasingly negative impact on both economics and ecosystems as the project scale increases. On the other hand, after modeling cellulosic ethanol plants at different scales, Gwehenberger and Narodoslawsky (2007) suggest that larger scale can improve economic and ecological efficiency (a) if more elaborate processes producing many different products are involved (which is difficult for small-scale projects) and (b) when more agricultural byproducts are available. When these conditions are not met, they suggest that small-scale projects with one product and powered by bioenergy from crops grown only for this purpose have a better balance between ecological impact and economical benefits.

SCALE AND SUSTAINABILITY—IMPLICATIONS FROM SYSTEMS THEORY

Giving equal weight to efficient use of resources, biophysical limits, and the fair distribution of benefits is crucial when the goal is to develop sustainable bioenergy solutions (Gowdy & Erickson, 2005). Systems theory has been suggested in a number of applications as an effective framework for assessing sustainability (e.g., Abel, 2004; Hjorth & Bagheri, 2006). This is because the theory is able to integrate various components into one assessment as it focuses on the interactions between individual components within a system in a coherent way. Another strength of the systems approach is its ability to incorporate wider system boundaries while also defining them precisely. Even complex systems in which different components influence each others' evolution can be effectively analyzed with this approach.

A bioenergy system can easily be described as a complex, adaptive system with the coevolving sub-systems of feedstock supply, conversion technology and energy allocation. These sub-systems are further embedded into an environmental, economic, and social context that is unique to each system. These systems involve agents that adapt and learn, thereby changing the systems from within (Buchholz, Volk, & Luzadis, 2007b; Luzadis, Volk, & Buchholz, 2009). Systems are only sustainable, can survive, and continue to function effectively and efficiently when they are resilient to change either from within or outside the system through protection or adaptation. Failure to pay attention to and address forces on one sub-system can lead to the failure of that sub-system and ultimately of the entire bioenergy system because the components are inextricably linked (Karekezi, 2001).

Systems approaches can be used at different levels of sophistication and with various qualitative or quantitative procedures (e.g., Hammond, 2003;

Buchholz et al., 2007b for references). A detailed, integrated, and quantified sustainability assessment of large- versus small-scale bioenergy projects is beyond the scope of this article (see, e.g., Odum, 1996). However, using a systems approach and drawing on systems theory can introduce new perspectives and highlight some of the differences between small- and large-scale systems that might be otherwise neglected. To frame this discussion, we present two separate case studies of bioenergy projects—one small-scale with 200-kW electrical output and one large-scale with 50-MW electrical output, both in operation or being developed in Uganda.

LARGE- AND SMALL-SCALE—A CASE STUDY ON BIOPOWER IN UGANDA

Uganda's economy is already overwhelming its meager electricity supply resulting in an increasing number of blackouts, unmet demand, high energy prices, uneven distribution, limited development opportunities, and inefficient electricity production. It is estimated that 34% of total private sector investment is used for fossil fuel-based electricity backup systems (Eberhard, Clark, Wamukonya, & Gratwick, 2005). Yet only 5% of all Ugandan households have access to electricity, which is one of the lowest rates in Africa (Eberhard et al., 2005). About 77% of Ugandans live rural areas (FAO, 2011). In 2008, only 4% of the rural population had access to electricity (International Energy Agency [IEA], 2011.). In order to put energy consumption in Uganda into perspective, it is necessary to take the non-monetary, traditional, non-electricity energy supply into account because about 90% of the total energy needs of Ugandans are supplied by fuelwood (Bingh, 2004).

Wood-based biopower systems could contribute to the development of the Ugandan electricity sector, especially in rural areas where electricity is currently lacking. In contrast to many other forms of modern bioenergy that may compete directly with forests for land, electricity generation from woody biomass can support sustainable forestry practices by utilizing low-grade wood from natural forests or perennial woody crops grown on marginal land (e.g., Siriri & Raussen, 2003). Its profitability has been demonstrated for decades and the technology has been established (e.g., Wiltsee, 2000). In addition, biopower from wood can have a very beneficial energy input to output ratio of 1:7–13, meaning that for every unit of energy invested through human activity, 7 to 13 units of useful energy are procured (Pimentel, 2001; Keoleian & Volk, 2005). This efficiency in energy production and its potentially low greenhouse gas emissions are another advantage of wood-based biopower systems in this age of global climate change (Mann & Spath, 1999; Keoleian & Volk, 2005).

The case studies used in this article compare a 50-MW power plant and a 200-kW combined-heat-and-power plant that are both fired by wood chips from dedicated fuelwood plantations in Uganda. Both of these Ugandan case studies are somewhat hypothetical in their own sense: The large-scale system is only in its planning stage and the small-scale system is discussed as an option for rural (household) electrification, but its data are derived from a rural industrial application. Nevertheless, the use and comparison of these two case studies enable us to explore and identify important issues and general trends. To date, only a feasibility study has been completed for the 50-MW plant (Figure 1) while the 200-kW plant (Figure 2) has been in operation for the last 2 yr. As the 50-MW plant has not been realized to date, Figure 1 shows a biopower system using a similar technology for a better understanding of the scale. Table 1 compares some of the general characteristics of the two systems that are often highlighted in conventional feasibility studies. Although the small-scale project depicted here does supply power and heat to a specific industry, it can also be developed and deployed for communities as well (Nouni, Mullick, & Kandpal, 2007).

Biopower Systems Nested in Larger Socio-Ecological Systems

The conditions of surrounding socio-ecological super-systems or levels in which the two bioenergy systems are embedded differ significantly, as

FIGURE 1 The 50-MW wood powered steam turbine McNeil Station, Vermont, USA (Source: Burlington Electric Department, 2011) (color figure available online).

FIGURE 2 The 200-kW wood gasifier (circled) at Muzizi Tea Estate, Uganda (Photo: Buchholz, 2007) (color figure available online).

provided in Table 1. For the 50-MW project, the electricity is delivered to the adjacent town of Gulu, not to the local consumers (Figure 3). The financing entity and the owners have an international background. The conversion technology is provided from abroad, and white collar jobs are advertised and usually filled internationally. The plant is expected to draw a blue collar workforce from across the region, potentially creating new communities in the vicinity of the plant. In contrast, the 200-kW project provides electricity and heat to local customers, and is mostly financed and owned by a national entity. Its white collar jobs are advertised nationally and very little migration of blue collar workers is expected (Figure 4). The environmental impacts—— although possibly differing in quantity—are made at levels that are similar to the larger power plant. For instance, in both cases, the emission of greenhouse gases is a global issue, while noise has only a localized impact.

Increasing Complexity with Increasing Scale

With increasing spatial scale, higher socio-ecological levels (global and regional/national) are involved to a greater extent (see Figure 3 and

TABLE 1 Characteristics of the Two Ugandan Biopower Case Studies

Net capacity (electric)	Units	50 MW[a]	200 KW[b]
Owner		International investment firm	National industry
Business concept		Power production only, selling electricity to the grid	Combined heat and power (CHP) for internal energy demand of a tea factory
Applied technology		Bubbling fluidized bed boiler with steam turbine	Wood gasifier with diesel engine
Implementation status		Feasibility study	Operating since May 2006
Energy efficiency	% electric efficiency (including heat)	30% (no heat application)	15% electricity only; 75% electricity and heat
Project lifetime	years	28	13
Electricity production costs	US$/kWh	0.10–0.13	~0.14
Total (and per kW installed) investment costs	US$ (US$/kW)	165 million (3,300)	450,000 (2,087)
Area needed for biomass production	ha	30,000 ha (15% native tree species)	51 ha (+ 80 ha for additional heat supply to dry tea
Biomass productivity	m^3 ha^{-1} yr^{-1}	25	30
Land use efficiency	ha/MW	600	635
Total (and per MW installed) direct jobs created	Total (jobs/MW)	>1,000 (20 jobs/MW) incl. fuelwood supply chain	12 (60 jobs/MW) excluding fuelwood supply chain
Other measurable social impacts		Active community develop-ment (schools, hospital, etc.)	No active community development

Note. The 50-MW project creates a considerable number of jobs and can promote specific community development such as building schools and hospitals. No such direct support for the local community comes from the small-scale project.

[a]Source: Buchholz, Volk, Tennigkeit, & Da Silva (2007).

[b]Source: Buchholz & Volk (2007).

Figure 4) and better techniques have to be developed to reduce associated uncertainties and risks of failure: the bigger the project, the better the techniques to respond to anticipated impact growing with scale (see also Pétry, 1990). This relationship between complexity and scale is evident in the longer planning and implementation phases of larger scale projects and the more stringent regulations to which they typically have to adhere. The 200-kW biopower system took 2 yr from planning to implementation and required only one permit from the national level in the form of an environmental impact assessment. On the other hand, the 50-MW project is still

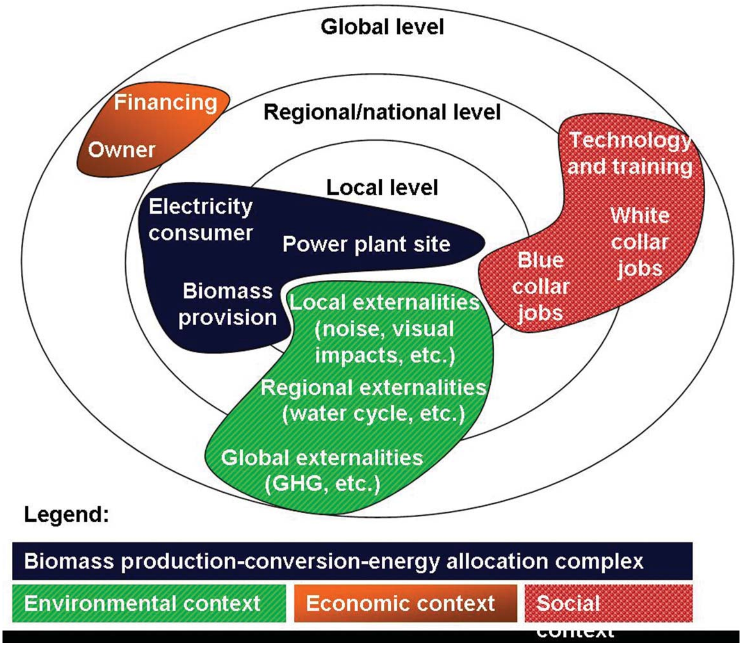

FIGURE 3 Socio-ecological levels engaged by a 50-MW plant in Uganda (color figure available online).

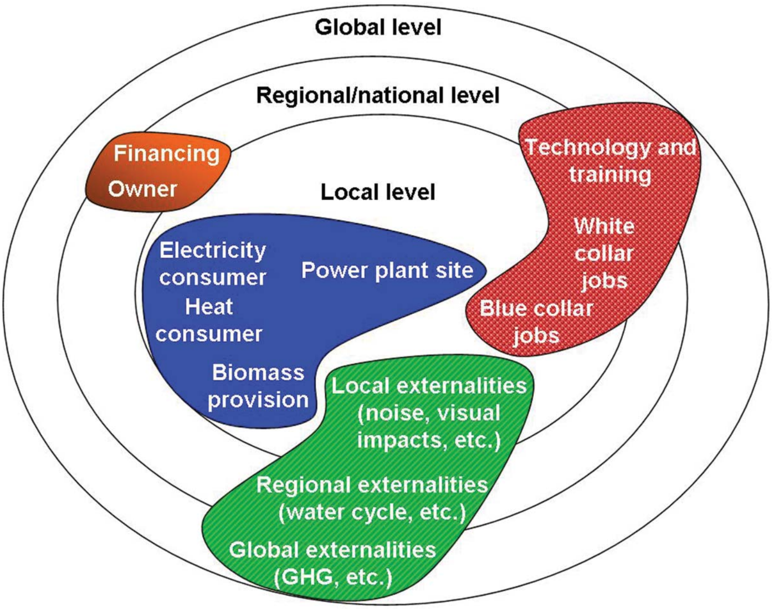

FIGURE 4 Socio-ecological levels affected by the 200-kW plant operating at a tea processing factory in Uganda (color figure available online).

at the stage of feasibility study after 2 yr of work. Thus, it might be more efficient and sustainable to support many small projects that are more easily replicated instead of one large project.

Time and Scale—Resilience Through Diversification

Another important aspect of bioenergy systems is their increasing longevity with increasing scale (Buchholz et al., 2007b). A small system (e.g., a 200-kW biopower system) can fulfill its purpose and become sustainable in shorter time scales than larger systems, in which several individual 200-kW biopower plants are connected to comprise a "virtual power plant" (Odum, 1988; Costanza & Patten, 1995; Holling, 2001). In other words, while the 200-kW biopower system is considered economically sustainable with a project life of 13 yr, the 50-MW project has a longer expected lifespan of up to three decades. When several small power plants are compared with one large plant, the projected shorter lifespan of smaller systems, their lower associated impacts in case of failure, and their spatial distribution altogether promote evolution and innovation of different technologies and approaches while hedging the risks. These facts further contribute to the system's overall resilience. On the other hand, the high investments necessary for the 50-MW project rely on established rather than innovative technologies. This implies that higher risks and less stringent sustainability criteria could be accepted for small-scale bioenergy systems in assessing its sustainability compared to large-scale projects (Norgaard, 1994; Voinov & Farley, 2007).

Energy and Resource Efficiency Aspects

Efficiency measures are often used as technical, expert-based, and objective criteria for system assessments. However, efficiency depends heavily on where systems boundaries are drawn and can involve a wide array of factors like energy, resources, investment/finances, natural capital, or human labor. Because of the diverse components involved or affected by efficiency measurements, it should not be seen as the sole criterion guiding decisions.

Efforts to include the wide array of factors associated with efficiency can often be confusing. For instance, looking only at electrical efficiency, the 50-MW technology fares better (see Table 1). However, while the 200-kW system utilizes the waste heat and generates an overall efficiency of 75%, the heat from the 50-MW plant would not be utilized. Moreover, the electricity of the 200-kW system is used on site so that transmission costs and transmission losses, though existent, are minimal compared to centralized large-scale power plants: The 50 MW-plant would rely on electrical distribution on a regional or national grid with losses from 10% (global average; World Alliance for Decentralized Energy [WADE], 2009) to over 30% in

Uganda (Ministry for Energy and Mineral Development, 2008), significantly lowering the overall efficiency of the system if the delivery of the electricity to the end user is included in the assessment. In other words, drawing the boundaries of systems on equal terms—including the corresponding subcomponents from biomass production to end use—for both small- and large-scale systems is a crucial step in the assessment when comparing both (see also, e.g., Karger & Hennings, 2009). Moreover, large units of energy are more prone to loss of efficiency when they are run at partial loads (e.g., Nouni et al., 2007 for biopower). For example, two small systems that together deliver the power of one larger system could have one of the systems shut down while the other runs at full capacity, resulting in one system of full efficiency delivering 50% of the total output (Lovins, 2002). These examples—the inclusion of heat use, transmission losses, and energy efficiency loss—demonstrate the critical role that system boundaries play when assessing systems and the importance of a systems approach in general. An efficiency analysis of an electricity system focusing on electricity generation at a power plant will result in very different outcomes than an analysis incorporating the electricity distribution and delivery to the end user as well.

Sustainable and reliable feedstock supply is a key to bioenergy systems of any kind or size. The 50-MW plant would need 600 ha dedicated to woody biomass production for each MW installed, while the 200-kW biopower system requires around 635 ha per MW installed (see Table 1). This nearly equal number is surprising for two reasons: (a) it is generally argued that large-scale system allows for a more efficient resource use through better conversion technology, and (b) only slightly lower biomass productivity (25 m^3 ha^{-1} yr^{-1}) is assumed for the large-scale plant than the small-scale system (30 m^3 ha^{-1} yr^{-1}). Part of this difference is associated with the design of the plantations. While the proposed plantations for the large-scale plant incorporate fire rows and roads built solely for the plantation, the plantations for the small-scale system are integrated into an existing infrastructure of roads and alternating field patterns, avoiding the need for firebreaks altogether. While the larger biomass supply for the 50-MW facility grown on 30,000 ha will be close to the plant, the average transport distance would be more than 7 km when the power plant is located in the middle of a 30,000-ha circle and provided by biomass from within this circle. In contrast, the smaller 200-kW system is supplied by biomass that is grown in 51 ha within 4 km of the facility, thereby significantly reducing the average biomass transport distances compared to the large-scale project.

Financial Aspects

There are a variety of tools that can be used to assess investment efficiency, but most commonly internal rate of return (IRR) or a payback period is used. While these figures are proprietary for the 50-MW project, they compete with a 30% IRR for the 200-kW system. For the 200-kW system, the payback period is only 4 yr and the projected lifetime is 13 yr. The large-scale system takes the lifetime of 28 yr to deliver its full profits, thus having a higher level of risk because of the long time frame.

Theoretical calculations for the larger system suggest an electricity price of 0.10 to US$0.13 cents per kWh while the smaller system produces electricity at a cost of US$0.14 (see Table 1). While this difference can be substantial (with the large system producing power at 8 to 40% less cost), it has to be kept in mind that distribution costs are not included in both systems and the projected electricity prices for the large-scale plant are still untested.

On the other hand, an advantage of the large-scale plant is that its size allows participation in the carbon credit market while the small-scale plant cannot easily sell its carbon credits in the market because of the disproportional overhead costs for a relatively small amount of carbon. However, this disadvantage of small-scale projects might be overcome by bundling several projects together and with simplified assessment methodologies (United Nations Framework Convention on Climate Change [UNFCCC], 2009).

Social Aspects

Figure 3 and Figure 4 illustrate the spatial level where financial decisions were made in both case studies. As the project size increases, the decision makers were less likely to be local. Participation of stakeholders is a key component of sustainability (Reed, Fraser, & Dougill, 2006), yet the increasing complexity of large-scale bioenergy projects typically involves a shift to more centralized decision making despite the greater number of stakeholders. Stakeholder participation at each level in a large-scale project is often seen as too complicated and either ignored or is relegated to public education rather than true participation (Farley, Erickson, & Daly, 2005). The risk of a disrupted social cohesion or even project failure due to such practices can be considerable (Upreti, 2004; Upreti & van der Horst, 2004). The Ugandan 50-MW large-scale project was focusing on negotiations with those few individuals in the region who owned large estates so that sufficient acreage for the fuelwood plantation could be obtained with minimal participation of other local residents. However, sustainability as a normative value is also based on individual risk perceptions and values, and is most effective when it involves participatory planning.

The large-scale facility would provide a considerable number of jobs (<1,000) in a location where no established community currently exists, thus triggering migration. On the other hand, small-scale plants are known for being situated (and being suitable) at the site of demand where people live and work already, therefore little migration occurs. Moreover, while the large system would create only 20 direct jobs per MW including the fuelwood supply chain, the small system did create in total of 12 jobs (which is equivalent to 60 jobs per MW installed) only at the plant, excluding the fuelwood supply chain operation. Additionally, the large-scale plant would be the only employer since they would operate the entire process from growing the biomass to producing electricity independently, while the small system consists of several entities that can separately employ people. This is partly based on the fact that the large scale of the operation depends on a more complicated, multi-stage logistics chain that requires a highly organized system. The more such processes depend on “just in time” delivery, the higher the risk that the supply will be disrupted and the plant will not be able to operate at full capacity. The small-scale system was based on a large wood yard for storage and many subcontractors who partly sell fuelwood but are mainly contracted to maintain plantations or harvest and transport the biomass. Thus the supply chain logistics was relatively simple and secure.

Larger scale power projects tend to have an urban bias since it requires large-scale consumption while keeping transmission costs down. The 50-MW plant site was chosen to be close to the second largest Ugandan town with around 120,000 inhabitants to provide additional electricity. Rural electrification with its intended development benefits in scattered settlements is more likely to be pursued with small-scale distributed power production. These small-scale systems often do not add additional power to a region but extend electricity services to formerly non-electrified regions. Thus it is more likely to address rural subsistence needs rather than urban consumption and alleviate the urban-rural distribution bias (see also Gowdy & Erickson, 2005 for a discussion of “welfare efficiency”). The standard of living of a rural household can be improved dramatically by providing a basic electricity service with relatively small amounts of inputs once the system is in place. About 80 kg of wood per person and year can provide a very generous base load of 30 kWh for a rural household of eight persons as well as electricity for basic community services (health care centers, schools, repair workshops, and mills), significantly improving the communities standard of living (Buchholz & Da Silva, 2010). In contrast, the same household consumes around eight dry tons of wood per year for construction, heating, and cooking (Buchholz & Da Silva, 2010). In comparison, the same 80 kg of wood producing electricity for an urban society would most likely have very little impact on the standard of living in urban households that are already connected to the grid. The small-scale plant at the Muzizi Estate exemplified this principle; its small size delivers improved electricity services to a rural (off-grid) demand.

The relatively small amount of wood (in comparison to other current uses of biomass) needed to provide a basic base load of electricity for a rural setting is also reflected in the impact of the scale in bioenergy projects on land demand. Improving basic living standards through biopower in rural settings applies little additional pressure on fertile land, which is an important issue in Uganda, a net food importer (Food and Agriculture

Organization of the United Nations [FAO], 2011), with an estimated 0.32-ha arable and pastureland per capita. Developing bioenergy projects on marginal land covering large areas can potentially improve the efficiency of land use while minimizing competition with food production. One study projected that between 300 and 700 EJ/yr could be produced worldwide in 2050 from biomass grown on abandoned and non-productive land (Hoogwijk, Faaij, de Vries, & Turkenburg, 2009) Considering the distribution of most of such marginal sites scattered across the landscape (slopes, degraded sites, etc.) in small patches, their use is more likely to occur in small-scale applications rather than large-scale biomass production relying in general on large and coherent tracts of land.

Impacts on the Ecosystem

Although both scales discussed above have ecological impacts, the extent of the respective impacts is difficult to compare between the two systems. The smaller scale system is easier to integrate into the surrounding land use pattern because the footprint of the facility and the area needed for fuelwood plantations is relatively small, while the large-scale system will result in more dramatic changes, affecting the land use in about 30,000 ha around the plant. While there are no imminent indications that the several small patches of fuelwood plantations for the 200-kW system destabilize the larger ecosystem they are nested in, the large-scale plantations required for the 50-MW plant would convert the current grassland and have created concerns about their negative impact on wildlife corridors, groundwater levels, fire risks, and ecological risks associated with monocultures and exotic tree species. It remains unanswered whether the distributed nature of plantations of the small-scale system might make up for the 6% higher land demand associated with it compared to the large-scale system (Table 1; 600 ha/MW for the large-scale system versus 635 ha/MW for the small-scale systems). Similarly, while the cooling water supply and discharge for the 50-MW plant would rely on the local Aswa River and seriously impact its hydrology, the low water demand for the 200 kW does not have a major hydrological impact (James Finlay Uganda, 2007). In addition, the threat to ecosystems caused by a sudden population increase is undeniable in the case of the 50-MW plant built in an area with a low population density. The large migration of people into a sparsely populated area that would occur with the jobs created by the large-scale power plant is likely to trigger a large, though indirect, negative impact on the surrounding ecosystems such as deforestation, as people harvest wood for personal needs and clear land for crop production. (Naughton-Treves, Kammen, & Chapman, 2007).

On the other hand, the large-scale system enables more effective control mechanisms such as measuring emissions and waste streams and putting a certification scheme in place to ensure sustainable forestry management (a stated goal in the 50-MW plant feasibility study is to obtain certification of its plantations through the Forest Stewardship Council). Such elaborate control mechanisms are prohibitively expensive for small-scale systems.

However, most of the ecological impacts need to be quantified more in detail to allow meaningful comparisons of large- versus small-scale. It has to be noted that the fairly high biomass productivity of 25 to 30 m^3 ha^{-1} yr^{-1} was assumed for both scales using mainly *Eucalyptus* spp. that demands intensive management practices including application of chemical herbicides and fungicides. The impacts of such practices on long-term sustainability are heavily debated (see, e.g., Pimentel et al., 2002), such as the long-term impact of such high-productivity plantation practice on soils.

CONCLUSIONS

The use of a systems approach to understand bioenergy systems can help elucidate the potential advantages and disadvantages of different scales. This approach goes beyond traditional cost-benefit analysis or environmental and social impact assessments and includes a broader array of factors. Large-scale bioenergy systems seem to be easier to control and regulate, are more likely to participate in schemes providing certification for sustainable practices, and potentially offer easily traceable community benefits. On the other hand, small-scale bioenergy systems promise an efficient use of resources, reduce environmental impacts from power production, are more likely to actively involve stakeholders, are more likely to deliver their benefits to the local rural communities, and offer more opportunities for innovation and learning. At the same time as offering affordable power, small-scale systems can be implemented in relatively short time frames and with potentially low investments. To increase the potential of small-scale bioenergy projects, the following steps might be valuable:

- To deploy small-scale bioenergy beyond industrial use, there is a need to create awareness among public authorities, investors, and project developers about the benefits of small-scale bioenergy systems in order to access capital and expert knowledge.
- Comprehensive quantification methodology, such as an energy analysis that allows direct comparison of the impacts of many small-scale bioenergy systems (a “virtual power plant”) versus a few large-scale ones, needs to be developed and deployed (Peng et al., 2008).
- Criteria and indicator frameworks to assess sustainability need to be developed for bioenergy systems to allow quick assessments. Such frameworks would need to include rules of how the criteria need to be examined to ensure sustainability by specifying performance thresholds or scales, and

specify which political entity would be responsible for implementation. Such frameworks are known and have been tested in forestry (e.g., Forest Stewardship Council, 2011a), carbon markets (Clean Development Mechanism, 2009), and fair trade (Fairtrade, 2009); and are capable of dealing with the comparable complexity in social, environmental, and economic contexts associated with bioenergy systems.

- When applying such criteria and indicator frameworks, systems theory suggests that small-scale bioenergy systems should be subjected to less stringent and elaborate assessments and rules than large-scale systems, not only to allow innovation and evolution of these systems but also for the lower risks and negative impacts associated with them. This has been already acknowledged for bioenergy production in general (e.g., Ecological Society of America, 2008) and put into practice in other systems. For example, cluster certification schemes for small projects are subject to less stringent rules for fair trade (Fairtrade, 2011), sustainable forestry (Forest Stewardship Council, 2009b), or carbon credit schemes under the Kyoto protocol (ENCOFOR, 2009).
- There might be valuable insights from international efforts to assess sustainability of bioenergy systems (e.g., Roundtable on Sustainable Biofuels, 2009) that could contribute to the discussion outlined in this article focusing on power and heat production from biomass. To better understand the socio-political context of bioenergy, sustainability criteria assessing social aspects of bioenergy systems might need further development (see, e.g., Buchholz, Volk, & Luzadis, 2009). On the same note, Bush (2008) argues that there is a need to embrace lessons learned from social science of natural resource use from agriculture and technology transfer during the green revolution.
- It appears that there is a trend toward large-scale bioenergy solutions and therefore developing small-scale, distributed electricity production capacity needs focused political support. For instance, the Renewable Energy Law of Germany compensates renewable electricity fed into the grid from smaller production facilities more generously than larger electricity produced at large-scale applications (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2011). In Uganda, political support of small-scale electricity production has been restricted so far to a tax waiver program for diesel fueled generators of 100 kW and above. Announced in 2006 and responding to the growing inadequacy of grid supply across the nation, this program was terminated in the fiscal year 2008–2009 (Nakaweesi, 2008). Similar programs for bioenergy systems could provide crucial incentives to stimulate their development. While the renewable energy policy of Uganda (Ministry of Energy and Minerals [MOEM], 2008) recognizes the connection between types of renewable energy and small-scale production—especially in rural areas—and

suggests numerous supportive measures and tools, effective support has been lacking. Although the electricity grid has been deregulated, current feed-in tariffs even during peak load times are below cost for both case studies discussed in this article (Electricity Regulatory Authority [ERA], 2011).

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