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Modeling the profitability of power production from short-rotation woody crops in Sub-Saharan Africa

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ABSTRACT

Increasing electricity supply in Sub-Saharan Africa is a prerequisite to enable economic development and reduce poverty. Renewable sources such as wood-fueled power plants are being promoted for social, environmental and economic reasons. We analyzed an economic model of a vertically integrated system of short-rotation woody crops (SRWC) plantations coupled with a combined heat and power (CHP) plant under Sub-Saharan African conditions. We analyzed a 5 MW (electric) base-case scenario under Ugandan conditions with a 2870 ha *Eucalyptus grandis* plantation and a productivity of 12 t ha^{-1} y^{-1} (oven dry basis) under a 5-year rotation. Plant construction and maintenance constituted 27% and 41% of total costs, respectively. Plantation productivity, carbon credit sales as well as land, fuel, labor & transport costs played an economic minor role. Highly influential variables included plant efficiency & construction costs, plantation design (spacing and rotation length) and harvest technologies. We conclude that growing 12–24 t ha^{-1} y^{-1} at a five year rotation can produce IRR's of 16 and 19% over 30-years, respectively. Reducing rotation length significantly reduced short-term financial risk related to frontloaded costs and relatively late revenues from electricity sales. Long-term feed-in tariffs and availability of a heat market played a significant economic role. The base-case scenario's 30-year IRR dropped from 16% to 9% when a heat market was absent. Results suggest a leveling-off of economies-of-scale effects above 20 MW (electric) installations. Implementation-related research needs for pilot activities should focus on SRWC productivity and energy life cycle analysis.

1. Introduction

Sub-Saharan Africa currently faces a major electricity shortage. Regionally, only 20% of the population of Sub-Saharan Africa has access to electricity [1]. Without access to electricity it is difficult to attain the Millennium Development Goals on poverty reduction and environmental sustainability [2]. Over 75% of the electricity produced in Sub-Saharan Africa is derived from coal or oil, with the share of renewables declining in the region [1]. In 2007, more than 50% or 200 MW of the power in Uganda was produced by emergency thermal generators with tariffs as high as 0.2 € kWh^{-1} and large carbon footprints [3]. Considering that 77% of Ugandans live in rural areas [4] and that these are in particular underserved with

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energy, i.e. less than 9% of the rural population had access to electricity [5] there is a strong need to increase renewable electricity production in rural centers.

Electricity production from biomass has a potential to improve human well-being by delivering energy on a long-term sustainable basis more efficiently than other sources of energy (Banerjee for India [6]; Buchholz and Da Silva for Uganda [7]). Woody-biomass based power plants ranging from a few kW to 50 MW are being investigated across the region (see Buchholz and Volk [8] or Buchholz et al. [9] for small-scale; Buchholz et al. [3] for large-scale). Most of these systems rely on fast-growing tree plantations or short-rotation woody crop (SRWC) systems where trees or shrubs are planted that have the ability to coppice and do not need to be replanted after a harvest. While many tree and shrub species exhibit coppicing abilities, *Eucalyptus spp*. has been widely used in commercial SRWC systems most notably for charcoal production in Brazil with over 45,000 km^2 of Eucalyptus bioenergy plantations in 2009 [10] or tea drying in Sub-Saharan Africa [8]. Historically, these systems applied rotation cycles of >5 years while more recent research investigates shorter rotation cycles due to increased harvest mechanization and improved planting stock [11].

Power systems based on woody-biomass such as SRWC are characterized by low material, energy and labor input, yielding energy returns on investment (EROI) between 43:1 [12] and 58:1 [13] at the plantation gate or 11:1 [14] for producing electricity. Pimentel et al. [15] reported of an EROI of 7:1 for a biomass power plant in the US sourcing wood from natural forests. Zanchi et al. [[16]] found SRWC-based gasifiers producing electricity to be advantageous in material and energy input compared with fossil-fuel based alternatives in Uganda. At the same time, decision frameworks to mitigate potential negative ecological and social impacts of such bioelectricity systems are being developed for the region [17,18].

However, economic studies on medium- to large-scale wood-based power systems are rare for the region. Several studies analyzed the economics at the small-scale power plant level [7–9]. Uncertainties on sustainably produced wood supply require vertically integrated business models with integrated feedstock production and power plant. A comprehensive economic analysis of the basic production schemes for SRWC-based power production in different tropical and sub-tropical regions or under various price structures is rare (van den Broek et al. for Nicaragua [19], Sims et al. [20] for New Zealand). We understand such a comprehensive economic analysis should at least consider components such as plantation economics, power plant engineering, and carbon finance. Other aspects such as viable energy distribution related business models and support policies should be investigated to attract investment, but this was not part of our investigation.

We modeled the economic performance of wood-derived electricity and heat production under various economic, biophysical, and management conditions using the Power-Forest 1.1 (Beta) model [21]. While the analytical framework can be applied to any dedicated woody feedstock plantations, we used *Eucalyptus grandis* in our case study since this species is widely used in Uganda and more local information on growth characteristics and plantation management is available compared to other potential tree species. Our simulation covered establishment, maintenance, harvest, transport of wood and electricity and heat production from SRWC systems under African conditions. We analyzed various site and spacing specific growth curves, treatments, and rotation lengths. Energy conversion technology varies little by region therefore our analysis focused on the biomass production part characterized by high variability while standard assumptions have been used for energy conversion and CDM AR related costs and revenues. The objectives of this simulation were:

- To identify the significance of SRWC economics within a vertically integrated business model incorporating plantation economics as well as power plant construction and maintenance costs representative for Sub-Saharan Africa;
- To identify the cost factors that have the greatest potential for improving the overall economics of a SRWC-based bioelectricity project.

2. Methods

2.1. Model description

Our model was designed for tree plantations using a coppice management system and subsequent conversion of biomass to electricity and usable heat. It analyzed the entire production chain from plantation establishment, maintenance, and harvest to the transport and storage of the biomass and energy production.

General input variables included total electricity output and conversion efficiency, inclusion of heat sales and carbon finance, project development and termination costs as well as skill-specific labor costs. Key variables for each of the biomass production modules (plantation establishment, maintenance, choice of harvest system, biomass transport, energy conversion, carbon finance) included incentive payments such as establishment grants and yearly rental payments in case of a land lease scenario.

We developed a species-, site- and rotation length-specific growth model that specified biomass growth, heating value, as well as the plantation design jointly with harvest productivity assumptions which are largely guided by plantation characteristics such as planting density and tree dimensions. We implied a continuous productivity throughout the plantation lifetime with no replanting requirements and changes in rotation length. Plantation establishment variables included site preparation such as clearing and road construction, per unit seedling costs and a manual planting system. Plantation maintenance cost variables covered pest control, inventory-related tasks, as well as labor, travel, equipment, and other supply costs. Establishment of the plantation was staggered over the rotation length of choice; for a 5-year rotation period only one-fifth of the total plantation area required was established in the first year with the remainder planted in the subsequent years until the full plantation is fully established. While initial and annual land costs will occur for the full plantation area starting with year one, plantation maintenance costs will increase in accordance with the progress in plantation establishment. As it is common practice on existing commercial SRWC plantations in Uganda, the maintenance module included costs associated with cutting back coppicing stems to one per stump for the manual and mechanized single-grip harvesting system (Fig. 1). This procedure maximizes diameter development while reducing stem density.

Three different plantation harvest systems were considered representative for tropical SRWC plantations:

- Manual felling, debranching, and cutting to length followed by carrying log segments manually to and stacking them at a skidding trail (each work step done by a separate laborer). A knuckle boom grab loads stems on roadworthy trailers; the wood is stacked and air-dried for two months at the power plant prior to being chipped and combusted;
- A single-grip harvester cuts, debranches and cuts stems to length, followed by mechanized skidding and loading of logs on roadworthy trailers; the wood is stacked and air-dried for two months at the power plant prior to being chipped and combusted;
- A track-mounted combined cut and chip harvester blows chips into roadworthy trailers; the chips air-dried for two months at the power plant prior to being combusted.

For the manual and single-grip harvester units, only log segments up to a top diameter of 5 cm were considered for extraction. Tops, branches, and leaves would be left on the ground to reduce soil nutrient depletion [22].

While efficiencies of each system relied on plantation characteristics (planting density, tree dimensions), they were not necessarily applicable at the same time. For instance, the combined cut and chip harvester might not be able to cut large-dimensioned trees. These assumptions are based on a project design where short transport distances keep transport with smaller and field-worthy trailers economically feasible and field conditions allow broad access by such trailers (no steep slopes, improved skidding trails etc.). For each harvest system, we modeled the appropriate hauling costs of logs or chips based on labor and equipment variables. The number of tractors and trailers was calculated based on the biomass harvest speed and plant consumption rate. The hauling distance was modeled on the assumption that the power plant is centrally located in the plantation but longer hauling distances were simulated as well. Machine costs for the harvest, transport, and bioenergy conversion module were based on a per unit basis with a depreciation period of five years. Loading and unloading of trailers are included in harvest and bioenergy production costs and not part of the transport costs.

Fig. 1 – 1.5 year old *Eucalyptus grandis* bioenergy coppice in Western Uganda. The SRWC system supplies biomass to a tea drying facility.

The size of the biomass storage area was calculated based on a two month supply of logs or chips to secure steady operation and a 20% moisture reduction (on a wet basis) independent of the time of the year [20,23]. We further considered capital and maintenance requirements for the woodyard and a combined heat and power or power-only plant, as well as internal electricity needs, capacity factor, labor requirements and options for plant site purchase or rental. Construction of the power plant was timed to start two years prior to the first harvest with two thirds of the costs occurring in the first year of construction and the remaining one-third occurring in the second and last year of construction.

We analyzed revenues from the sale of temporary Certified Emission Reductions (tCERs) providing a 20-year carbon sequestration commitment. Due to the high variability in carbon assessment schemes, we applied a very basic calculation only and did not consider carbon accounting methodology-specific eligibility criteria. Potential carbon credits from fuel-switch activities replacing fossil-fuel have not been considered since reliable data was not available.

We used the pre-tax Internal Rate of Return (IRR) and Net Present Value (NPV) for a project life of 10-, 20- and 30-years as economic performance indicators besides various figures on production costs, revenues, earnings, and profits on a unit and area basis. Further output numbers included total permanent positions created and startup costs required (including all costs up until electricity is produced for the first time). We modeled a best-case scenario based on a 10% increase in revenues and a 10% decrease in costs as well as a worst-case scenario including a 10% decrease in revenues and a 10% increase in costs.

2.2. Base-case scenario

The base-case was modeled on a 5 MW (electric) combined heat and power case study in Uganda (Table 1). We assumed a purchase of the required land for both the plantation and plant site. The plantation design was based on a 5-year rotation cycle using *Eucalyptus grandis* with a productivity of 12.2 t ha^{-1} y^{-1} (Table 2). Logs would be manually felled and then chipped at the plant site. Costs used in the base-case scenario for standard plantation operations such as herbicide applications and plowing and disking are based on 2011 rates for Uganda. While revenue from the liquidation (sale of land at purchase price only) at the end of the project lifetime

Table 1 – Selected input variables used for the base-case scenario. For details on the plantation growth model and harvest productivity see Table 3. For an exhaustive list of input variables see Supporting information Tables S1–7.

	Variable description	Unit	Values
General variables	Unskilled labor	€ y^{-1}	675
	Skilled labor	€ y^{-1}	5400–10,800
	Management	€ y^{-1}	32,000–48,000
	Indirect labor costs	% of direct labor costs	35%
Plantation	Plantation size (incl. roads etc.)	ha	2870
	Rotation length	Y	5
	Land cost	€ ha^{-1}	300
	Planting stock costs per seedling	€	0.05
	Fertilization per rotation	€ ha^{-1}	110
	Roads (and fire strips)	m ha^{-1}	10 (90)
	Road construction costs	€ m^{-1}	16
Harvest	Manual harvest – see Table 3 for details		
Transport	Transport distance	km	3
	Harvest and transport losses		5%
	Fuel consumption	km L^{-1}	4
	Fuel price	€ L^{-1}	1.0
	Tractor-trailer costs (three trailers per tractor)	€ km^{-1}	2.0
	Max. trailer capacity	m^3 (t)	40 (30)
Bioenergy production	Net electric (heat) output	MW	5.0 (9.9)
	Electric (heat) conversion efficiency		30% (60%)
	Capacity factor		85%
	Lower heating value at time of combustion (30% moisture content)	MWh t^{-1}	4.4
	Electric power capital cost	€ MW^{-1}	2,500,000
	Heat recovery capital cost	€ MW^{-1}	500,000
	Woodyard equipment	€	540,000
	Biomass storage losses	Logs/chips	1%/3%
	Electricity (heat) tariff	€ MWh^{-1}	100 (35)
Carbon finance	Price per t of carbon dioxide equivalent	€	5
	Initial carbon assessment costs	€	100,000
	Carbon monitoring costs	€ (every 5 years)	10,000

Table 2 – Input variables analyzed on their impact on overall project profitability. Ranges show the input numbers used for the sensitivity analysis.

Variables	Unit	Range
General		
Biomass yield	t ha^{-1} y^{-1}	1.1–26
Harvest costs	Dependent on stand conditions, see Table 3	
Rotation length	y	1–5
Planting density	Plants ha^{-1}	1588–10,000
Establishment grants	% of total establishment costs	50%–100%
Tariffs electricity	€ MWh^{-1}	70–130
Tariffs heat	€ MWh^{-1}	0–40
Electric capacity	MW	1–50
Electric conversion efficiency		20%–40%
Land costs	€ ha^{-1}	300 ± 30%; purchase vs. lease
Fuel costs	€ L^{-1}	1 ± 30%
Labor costs		±30%
Transport distance	km	2–50
Carbon price	€ per of t carbon dioxide equivalent	0–30

was considered in the base-case scenario, plantation removal costs were not considered. The power plant would start producing electricity in the 7th project year coinciding with the first biomass harvest and would produce power for 24 years. Table 3 lists variables that were adjusted in regard to the base-case scenario to perform an economic sensitivity analysis.

Table 2 outlines growth assumptions for *E. grandis* for three site productivities based on growth models developed for Uganda [28]. The goal of this growth model, which only considers stem biomass (see Section 2.1), was to maximize volume production (rather than tree diameter) based on a given rotation length. The planting density was optimized towards a density index of 75% when competition for light starts and self-thinning sets in at the end of the rotation period. Optimal planting densities reported for *Eucalyptus spp*. range from 2000 [24] to 5000 ha^{-1} [25] for 2–5 year rotations, while trials include densities as high as 40,000 plants ha^{-1} [26]. We analyzed site productivities corresponding to dominant tree heights or a site index (SI) of 25, 30, and 35 m at an age of 10 years. The mean annual productivity peaks in year 3, 4, and year 6 at a SI of 35, 30, and 25, respectively, which corresponds to findings of Stape et al. [11] on *Eucalyptus spp*. plantations in Brazil. We assumed validity of the growth model beyond the first rotation as coppice shoots were trimmed to one per stump (see Section 2.1) for all harvest systems except the cut and chip harvester system. Increased productivity has been

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Table 3 – Plantation growth model and harvest system productivity for *Eucalyptus grandis* for a site index (SI) of 25, 30 and 35 based on Alder [27]. Harvest systems are described in Section 2.1; 'n/a' indicates that a given harvest system is not suited for the specific plantation characteristics.

	Plantation growth model						Harvest productivity		
	Rotation length, y	Productivity[a], t ha^{-1} y^{-1}	Total biomass standing, t ha^{-1}	Planting density, plants ha^{-1}	DBH[b] at harvest, cm	Dominant height at harvest, m	Cut and chip harvest, h ha^{-1}	Single-grip harvest trees, h^{-1}	Manual harvest,[c] trees h^{-1} person^{-1}
SI 25	1	1.1	1.1	10,000	1.3	4.2	0.9	n/a	n/a
(base-case	2	8.1	16.2	9323	4.0	8.6	0.9	n/a	45
scenario)	3	10.8	32.3	5441	6.4	12.1	0.9	n/a	40
	4	11.8	47.3	3901	8.3	14.8	n/a	n/a	40
	5	12.2	61.0	3091	10.0	17.2	n/a	80	35
SI 30	1	5.3	5.3	10,000	2.5	6.1	0.9	n/a	n/a
	2	14.8	29.7	5829	6.0	11.6	0.9	n/a	40
	3	17.2	51.7	3597	8.9	15.6	0.9	n/a	35
	4	17.8	71.2	2669	11.1	18.8	n/a	80	30
	5	17.7	88.6	2166	13.0	21.4	n/a	80	25
SI 35	1	15.8	15.8	9476	8.5	3.9	0.9	n/a	45
	2	24.3	48.5	3813	15.1	8.5	n/a	80	35
	3	25.6	76.7	2487	19.6	11.7	n/a	80	30
	4	25.1	100.5	1911	23.1	14.2	n/a	75	20
	5	24.2	120.8	1588	26.0	16.2	n/a	70	20

a Mean annual productivity considering only stem biomass to a top diameter of 5 cm (except one year rotation).
b Diameter at breast height (1.3 m).
c Using a chainsaw or brushcutter; including felling, debranching and cutting to length.

reported for subsequent harvests following the first rotation [24], suggesting that total productivity throughout the project lifetime might be even higher than assumed in this study. We assumed a constant harvest productivity for the cut and chip harvester system as research indicates that productivity of these systems is more dependent on equipment reliance or plantation design dictating machine turning frequency and time through row lengths and the size of headlands rather than biomass stand volume [33].

It should be noted that *E. grandis* is certainly not an appropriate SRWC species across Uganda. It is nevertheless the only species on which information is available in Uganda. Any tree species with coppicing abilities and reasonable growth rates is in general suitable for use in the PowerForest model.

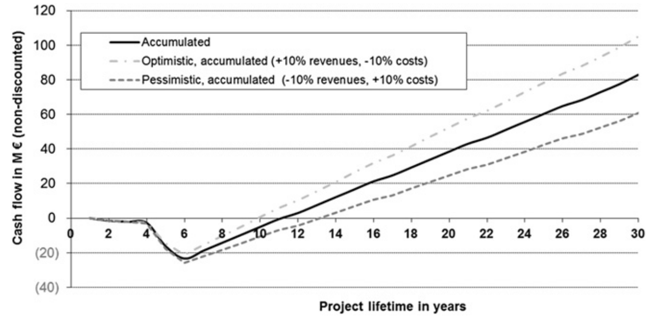

Fig. 2 – Undiscounted accumulated cash flow over the total project life of the 5 MW (electric) base-case scenario.

3. Results and discussion

3.1. Economics of the base-case scenario

The project would require an investment of 23.402 million € spent over the first 6 project years with the bulk spent in year 5 and 6 during plant construction. The base-case scenario's IRR over the total project's lifetime of 30-years is 16% (Table 4). Establishment costs from the start of the project through to the first harvest are 751 € ha^{-1}. The payback is reached in the 12th year (Fig. 2). Discontinuing the project after 11 years would render the project unprofitable with an IRR of −5%. However, the profitability after 20 years is only two IRR percentage points less than over a 30-year period. In other words, a loss of the project after 20 years constitutes significant losses in revenue but would nevertheless be profitable and therefore reduce investment risk considerably. In the best-case scenario, the payback period is reached in the tenth project year while the worst-case scenario projects the payback period on the 14th year. Total biomass production costs over the full project lifetime are 30 € t^{-1} including land (3.3 € t^{-1}), establishment (2.7 € t^{-1}), maintenance (9.3 € t^{-1}), harvest (12.9 € t^{-1}) and transport costs (2.1 € t^{-1}; see Supporting information Table S1–7).

Plant construction, plant maintenance and biomass harvest are the main costs making up 28%, 38% and 14% of the total undiscounted costs (Fig. 3). Plantation establishment and maintenance costs (land purchase, establishment and maintenance) play a less significant role accounting for less than 17% of expenses. 59% and 41% of revenues come from electricity and heat sales, while the sale of carbon credits related to afforestation and reforestation activities and sale of land at project termination account for only 0.2% and 0.6%.

Table 4 – Key output variables for the financial analysis of the 5 MW (electric) base-case scenario.

Output variable	Unit	Project life		
		10 y	20 y	30 y
IRR (10-, 20-, 30-y)	%	−5%	14%	16%
NPV[a] (10-, 20-, 30-y)	€	−6634	4434	8701
Permanent full-time jobs created[b]	–	196	196	196
Plantation size (incl. roads etc.)	ha	2870	2870	2870
Plantation establishment costs	€ ha^{-1}	751	751	751
Total startup costs[c]	k €	23,402		
Average revenues per year	k € y^{-1}	2551	4427	5052
Harvest costs	€ t^{-1}	12.9	12.9	12.9
Biomass production costs	€ t^{-1}	63	34	30
Transport costs[d]	€ t^{-1}	2.1	2.1	2.1
Electricity production costs	€ MWh^{-1}	255	73	42
Heat production costs	€ MWh^{-1}	27	8	5

a Using a discount rate of 10%.
b Post-establishment.
c All costs accumulated until first unit of electricity is produced.
d At a hauling distance of 3 km.

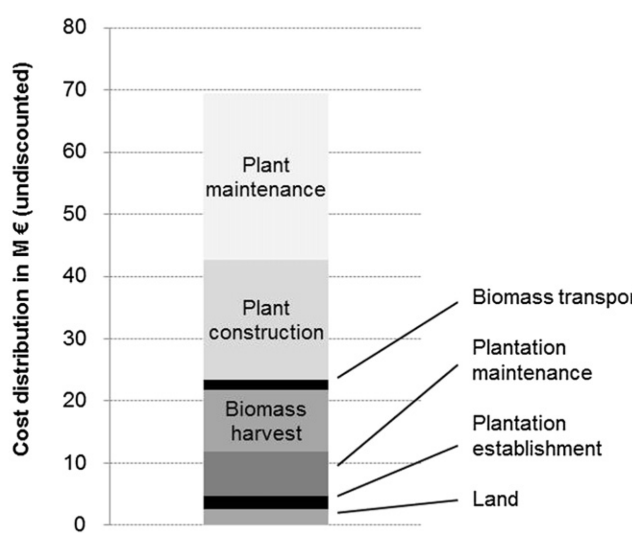

Fig. 3 – Distribution of total production costs (undiscounted) over the whole project life of 30-years for the 5 MW (electric) base-case scenario. Cost for plantation removal, carbon certification and verification as well as plant maintenance were insignificant.

The project would create 191 permanent full-time labor and 5 management positions, respectively, once the plantation is fully established (see Fig. 4). Most of the positions would be associated with harvest activities (124) and biomass plant maintenance (38).

3.2. *Variations to the baseline scenario*

3.2.1. *Rotation length and harvest system*

Biomass production costs including land, establishment, maintenance, harvest, and transport costs would account for 34% of total project costs. 42% of those biomass production costs are harvest costs (12.9 € t^{-1}, see Table 4). Reducing harvest costs might therefore affect the project's cash flow considerably. The mechanized alternative (single-grip harvester system, 115 € t^{-1}) is not profitable (2% IRR over 30-years) in the base-case scenario compared with a manual harvest due to the small individual tree diameters even at a five year rotation (Table 2). An alternative could be to reduce rotation length which would reduce stem size at the time of harvest and therefore allow for a mechanized cut and chip harvest system also reducing harvest labor costs. But potentially most influential for the overall project profitability is the late electricity production start in the 7th project year caused by a five year long plantation establishment period. Therefore, it might be of interest to reduce the rotation length despite losses in plantation productivity. Another option might be to establish a five year rotation design but harvest sections already after two or three years in the early project phase to allow the plant to come online as soon as possible, though with an initially reduced capacity.

Reducing the rotation period from 5 to 3 years and changing the harvest system from a manual to a mechanized one using a cut and chip harvester reduces harvest costs to 6.3 € t^{-1}, reduces the post-establishment permanent labor workforce to 66 (down from 191, Fig. 4), but increases the required plantation size from 2870 ha to 3177 ha. These changes increase the 30-y IRR by 1% point to 17% (Fig. 5). However, allowing the power plant to go online three years earlier than the base-case scenario increases the 10-year IRR significantly by 9% points to 4%; therefore reducing the project's economic risk considerably. Compared with the base-case scenario, the gain in short-term profitability is balanced in the long-run by the fact that the combined plantation establishment maintenance, and transport costs increase by 31% from 14.1 to 18.5 € t^{-1} which is not so much a result of the increased plantation size but more influenced by the lower density of chips compared with logs are transported.

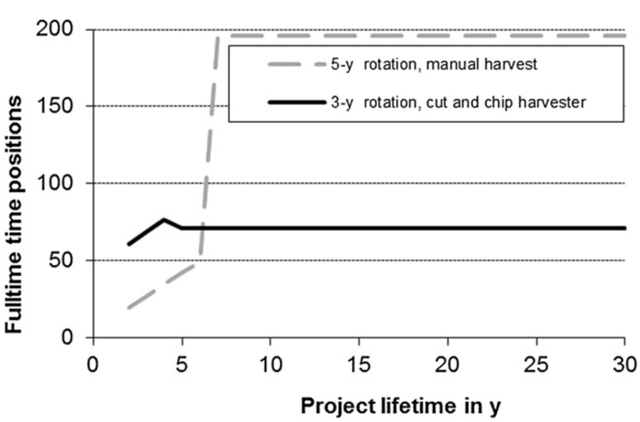

Fig. 4 – Full-time positions per year during the project's lifetime for the base-case scenario (5-year rotation, manual harvest) and a 3-year rotation scenario with a cut and chip harvester assuming the same site productivity (SI 25, see Table 2). A rapid plantation establishment with increased planting densities in the 2-year rotation scenario causes an initial high labor requirement. Positions associated with power plant construction are not included.

3.2.2. *Site productivity*

Fig. 5 further details how site productivity in combination with harvesting systems influence the project's profitability. Results suggest that rotation length and to some degree site productivity has only limited influence on a project's overall profitability. Instead, matching harvest technology to plantation design (spacing and rotation lengths) and productivity seems to be paramount. All site productivity scenarios were capable of producing a 30-year IRR of >16%. Increasing site productivity from SI 25 to SI 35 increases the maximum IRR from 17% to 19% (3-year rotation with a cut and chip harvesting system for SI 25; 3–5-year rotation harvested manually for SI 35). Several harvesting systems might yield positive returns for a given productivity and rotation length. Nevertheless, switching from one harvesting system to another can change the IRR drastically. For instance, harvesting a 3-year rotation system with a high productivity of 24 t ha^{-1} y^{-1} (SI 35) with a single-grip harvester instead of a manual harvesting system reduces the IRR from 19% to 9%. In general, the manual harvest system produces highest IRRs for longer rotations. Plantation design decisions prior to establishment are crucial as options to switch from one harvest system to another are limited as plantation design and size are geared towards maximum returns for a given harvest system in terms of planting density and tree diameter. It has to be noted that these results are highly sensitive to harvest productivity assumptions as well as site productivities. Therefore, extensive research on matching species with site productivity is essential to reduce uncertainties concerning harvest and plantation productivity of a specific project under review.

High planting densities for 1–2 year rotations are not well researched and might produce unnecessary initial establishment costs as well as increased harvest costs due to a lower mean stem diameter. Reducing planting density from 9323 N ha^{-1} to a more traditional density of 3000 ha^{-1} for a one year rotation at a site productivity corresponding to SI 25 reduces establishment costs from 1141 to 747 € ha^{-1} and increases the 30-year IRR by 1% point.

3.2.3. *Financial incentives*

Electricity production from biomass receives increasing support by governmental and non-governmental institutions based on a range of benefits such as its traits being a local or renewable energy source. Establishment grants as well as favorable tariffs above market prices are two widely used financial incentive mechanisms to spur its adoption. Providing an establishment grant covering 50% or 100% of plantation

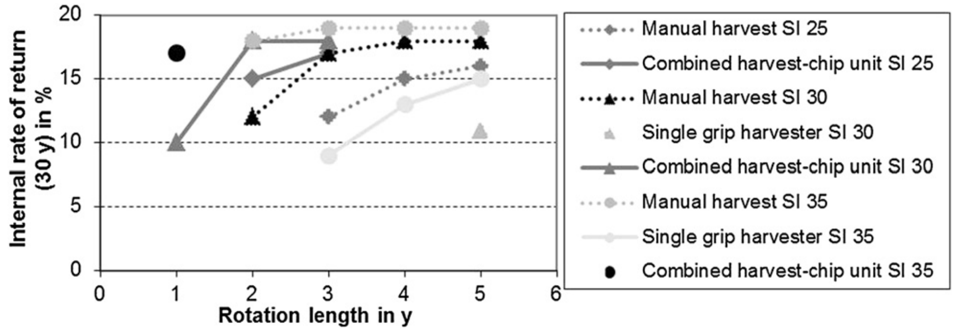

Fig. 5 – Profitability over the total project's lifetime of 30-years for different harvest techniques and rotation lengths and under different site productivity assumptions.

establishment costs (up to 751 € ha^{-1} or 2,071,458 € total) would increase the IRR by 1–2% points. Alternatively, the funds available to a grantor might be invested in providing an increased tariff. In contrast to an establishment grant, this incentive would be paid over time and be tied to the electricity production rate. To make both incentives comparable in costs over time we assumed that the funds (50%–100% of 2,071,458 €) would be available for an establishment grant at the start date of a project or alternatively available over time in terms of an increased tariff and discounted at an annual rate of 10%. Based on these assumptions, an increased tariff of 125–249 € MWh^{-1} would be available additional to the 100 € MWh^{-1} base-case revenues considering a 50% or 100% establishment grant; resulting in a 30-year IRR of 29–40%. Meanwhile, establishment grants might still be favorable to an investor to reduce overall startup costs and therefore investment risks.

3.2.4. *Tariff for electricity and heat*

In the base-case scenario revenues from heat sales (35 € MWh^{-1}) constitute 41% of total revenues. Fig. 6 outlines how changing heat sales impact the project's overall profitability based on three scenarios differing in electricity tariffs (70–130 € MWh^{-1}). Excluding heat sales (as well as capital costs for a heat recovery unit) would reduce the 30-year IRR of the base-case scenario by 7% points to 9%. Selling heat at 10 € MWh^{-1} can result in a decreased IRR (130 € MWh^{-1} electricity scenario) compared to a power-only scenario only, as heat sales are not offsetting additional costs from a heat recovery installation. A tariff for electricity of 70 € MWh^{-1} would require a tariff for heat of at least 28 € MWh^{-1}in order to result in a 30-year IRR of 10% or more. Furthermore, having no option to sell heat might require additional costs to install cooling technology which can be substantial in the humid tropics. Markets for steam- or hot-water driven cooling demand could substitute for absent heat markets.

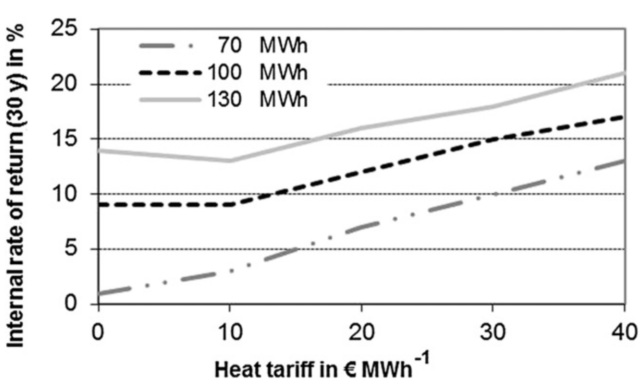

Fig. 6 – The impact of tariffs for heat on overall project IRR. Three different tariffs for electricity are considered.

3.2.5. *Plant capacity and electric conversion efficiency*

Capital costs of the power plant constitute 27% of total project cost assuming 3,000,000 € MW^{-1} for the installation of CHP technology. Biomass power plants as big as 50 MW have been analyzed under East African conditions [8]. Economies-of-scale are regularly used to decrease capital costs per MW unit installed while increasing electric conversion efficiency. Based on Sievers [29] and Everett and Billington [30] who assumed a 23% and 16% cost reduction when doubling capacity, respectively, we assumed a 20% decrease in capital costs when doubling plant capacity (Fig. 7). We further assumed an increase in maintenance costs in a linear relationship with scale; transport distance was linked to plantation size requirements. Depending on electric conversion efficiency and plant size, plantation sizes varied from 431 to 861 ha for a 1 MW (electric) plant to 21,525 to 43,051 ha for a 50 MW (electric), plant (40% heat and 20% electric conversion efficiency, respectively).

Fig. 7 shows how the IRR develops with increasing scale under three different electric conversion efficiency scenarios. While all three efficiency scenarios show considerable gains in IRR when increasing the scale from 1 to 20 MW, gains in IRR level off beyond 20 MW (electric) especially for technologies using lower conversion efficiencies. This leveling-off can be mainly attributed to the smaller capital cost-gains once a 20 MW size is exceeded. There might be slight economies-of-scale beyond the 20 MW scale when considering decreasing maintenance costs on a per unit basis and project transaction and management costs. In our analysis we assumed that management costs are linearly related to capacity.

It also should be noted that conversion efficiencies often increase with scale. The low-efficiency scenario (20% electric conversion efficiency) might be therefore more realistic for plant sizes <5 MW (electric) while the high-efficiency scenario

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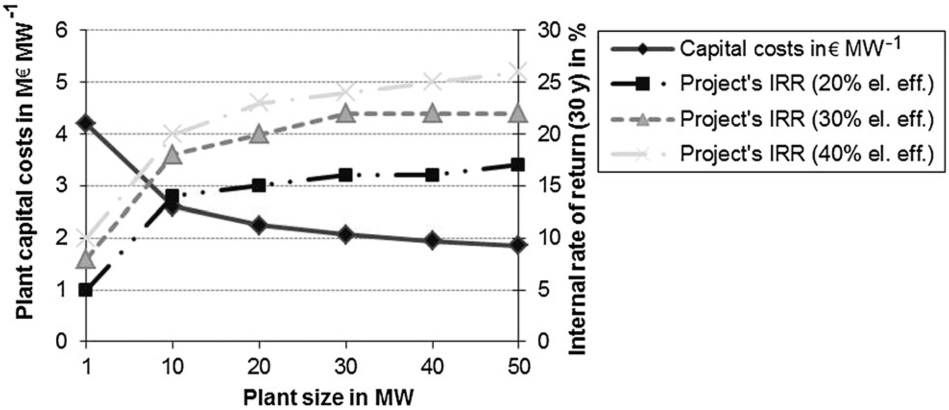

Fig. 7 – Financial analysis of economies-of-scale under various electric efficiency scenarios. We assumed capital costs of 3,000,000 € MW^{-1} for a 5 MW (electric) CHP plant excluding land costs and a reduction of capital costs by 20% when doubling plant size.

(30% and 40% electric efficiency for proven and currently researched technology, respectively) might be more representative of larger plants. However, highly efficient gasification systems [31,32] or technology using the organic Rankine cycle are increasingly becoming commercially competitive in the lower capacity range. In conclusion, land availability, energy demand especially for heat, price spans between heat and electricity tariffs as well as socio-economic considerations might have a larger influence on a project's size than financial gains through economies-of-scale [33].

3.2.6. *Land costs*

Land costs are often positively related to site productivity. However, we refrained from discussing both variables jointly as the nature of this relation is difficult to quantify across the region. Also the impact of other factors such as land availability in large tracts, as well as non-yield related biophysical (e.g. slope) and socio-economic factors (e.g. secure land titles, vicinity to energy demand or grid lines) on regional land pricing is highly variable.

Decreasing land costs by 30%–200 € ha^{-1} did change the 30-year IRR by less than 1% point. Increasing the land costs up to 406 € ha^{-1} would decrease the 30-year IRR by less than 1% point. Another option to modify land costs is changing from a 'land purchase' scenario (300 € ha^{-1} land price, 20 € ha^{-1} y^{-1} annual administration costs) to a 'land lease' scenario (10 € ha^{-1} initial costs to secure land titles, 50 € ha^{-1} y^{-1} annual lease) for both plantation area (2870 ha) and plant site (3.0 ha). This land lease scenario would leave the 10-, 20-, and 30-year IRR unchanged. The total startup costs would drop by 2% to 23,000,113 €. Results suggest that land price and property structure (land purchase vs. lease) play a minor role in a project's profitability under Sub-Sahara African conditions. Other considerations such as risk management and long-term commitment of land owners might play a dominant role in land-access decisions.

3.2.7. *Fuel and labor costs*

The economics of energy production from renewables such as biomass power are often sensitive to volatile fossil-fuel markets. Diesel fuel is the major source of fossil-fuel consumption in SRWC systems [13]. Increasing or decreasing Diesel price by ±30% from 1.0 € L^{-1} would increase/decrease harvest costs by ±1.1 € t^{-1} or ±6% (from 12.9 € t^{-1}) while leaving transport costs per t unchanged. This modification would not change the project's IRR. Only an increase in diesel fuel price by 90% to 1.9 € L^{-1} would decrease the 30-year IRR by 1% point. This result suggests that even high fluctuations in fuel costs play a minor role in the overall project's profitability despite the significant role that harvest costs play in the project's cash flow and the fairly high influence of diesel fuel price on harvest costs. Compared with manual harvest systems, highly-mechanized harvest designs are more susceptible to volatile fuel prices: increasing fuel costs by 30% for a 3-year rotational system with a cut and chip harvester did not reduce the overall 30-year IRR. Only an 80% increase in fuel costs decreased the IRR by 1% point. However, only direct fuel costs have been considered in this analysis. A full energy life cycle analysis [22] would also need to take indirect fossil-fuel consumption into account for e.g. fertilizer production, plant construction and equipment manufacturing. Meanwhile, increasing fossil-fuel costs also drive competing fossil-fuel based power production up which can improve the competitiveness of renewable energy systems.

Labor costs (excluding management) account for 21% of total undiscounted costs over the 30-year project lifetime. Compared with the base-case scenario, changing the labor costs by ±30% would change the 30-year IRR by 0/+1% points. While labor costs play a significant role in the project budget, drastic changes seem to affect the project's profitability to a limited extend. This is especially interesting considering that the base-case scenario is very labor intensive compared with other scenarios using more mechanized harvest systems.

3.2.8. *Transport distance*

Transport costs account for 2.3% of total project costs. In the base-case scenario we assumed a transport distance of 3 km resulting in transport costs of 2.1 € t^{-1}. Reducing stand density due to a change in rotation length or site productivity

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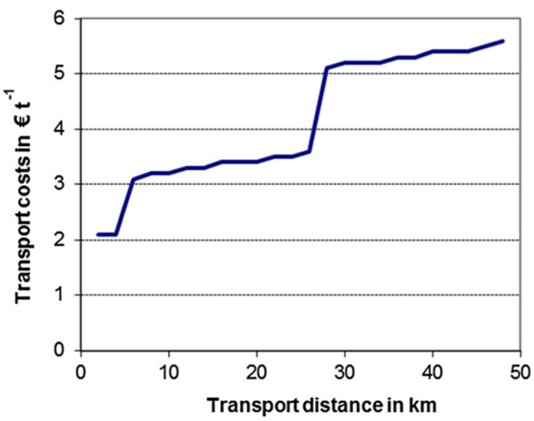

Fig. 8 – Transport distance and its relation to transport costs. We assumed a transport of logs and a tractor pulling two trailers with a total transport capacity of 37 t. Requirements to employ an additional transport unit to assure a minimum daily delivery rate cause drastically increasing transport costs when exceeding 4 and 26 km.

or increasing plant capacity (Section 3.2.5) can increase transport distance considerably. Fig. 8 shows the relationship between transport distance and transport costs. While transport costs nearly tripled when increasing transport distance from 2 km to 50 km, the project's 30-year IRR changed by less than 1% point up to a transport distance of 26 km. While playing a significant role in biomass costs, transport distance plays a limited role for the overall project's profitability. These results might for instance encourage managers to locate the power plant close to a heat consumer rather attempting to locate the plant in the center of a biomass plantation to reduce transport costs.

3.2.9. *Carbon credit sales from CDM AR activities*

Sale of carbon credits at 5 € per t of carbon dioxide equivalent account for 0.2% of total revenues (296,278 €) and 0.2% of costs (130,000 €). Removing sales of carbon credits under the conditions as outlined in the base-case scenario would leave the 30-year IRR unchanged while decreasing the 10-year IRR

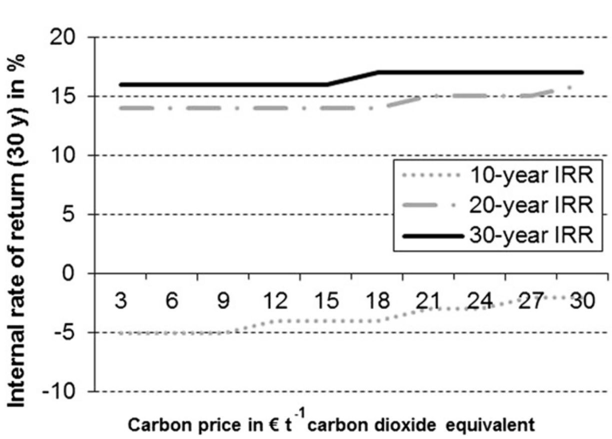

Fig. 9 – Carbon credit price and its influence on overall project profitability.

by 1% point. Fig. 9 shows that sales of carbon credits will play a minor role in the projects profitability even when increasing carbon credit prices 7-fold. Exceptional carbon prices of up to 30 € per t of carbon dioxide equivalent as paid on rare occasions in 2010 [34] would change the 30-year IRR by 1% point. However, these high priced carbon credits might be only possible under commitments exceeding a 20-year carbon sequestration time span. In contrast and if eligible, carbon credit sales derived from fuel-switch projects such as replacing oil-derived electricity systems with biomass power might play a superior role in the project's economics compared with CO_2 sequestration occurring at the plantation.

4. Conclusions and recommendations

Electricity production from woody-biomass is increasingly considered a viable option to increase electricity access in Sub-Saharan Africa. However, no commercial SRWC-based electricity system is being installed to date, though in a number of countries respective investments are under investigation. The goal of this study was to simulate the profitability of SRWC-based electricity production in a range of 1–50 MW (electric) under conditions typical for the region. For the 5 MW (electric) base-case scenario, plant construction and plant maintenance were the main expenses associated with the project making up 28% and 38% of total undiscounted costs. In general, biomass production costs (except harvest) played a minor role in the overall project economics. However, plantation management and design such as rotation length had a considerable influence on project profitability. For instance, shortening the rotation length can significantly reduce the project's short-term investment risk. In the base-case scenario, the 10-year IRR increased from −5% to 4% when reducing the rotation period from 5 to 3 years and switching from a manual harvest system to a mechanized one. This increase in the short-term IRR can be mainly attributed to the fact that the power plant would go online and generate revenues two years earlier. Long-term profitability remained fairly constant (30-year IRR 16%–17%).

In the base-case scenario the (manual) harvest system accounted for 14% of total project costs (12.9 € t^{-1}). The economics of harvest systems and choice of technology are driven by rotation length and site productivity which in turn dictate plantation design such as planting density and plantation size. Reducing rotation length to three years decreases stem size and therefore would allow to employ a cut and chip harvester at reduced costs (6.3 € t^{-1}).

Tariffs for electricity and heat played a significant economic role. The base-case scenario's 30-year IRR dropped from 16% to 9% if no heat sales were included. An electricity tariff of 70 € MWh^{-1} would require a heat tariff of >27 € MWh^{-1} to achieve a 30-year IRR of >10%. Feed-in tariffs for bagasse-fired power plants range from 38 to 48 € MWh^{-1} [35]. Site productivity (12–24 t ha^{-1} y^{-1} for a 5-year rotation), land, plantation establishment and maintenance, transport distance, fuel, and labor costs as well as revenues from carbon credit sales played a limited role in the overall project's profitability.

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Economies-of-scale increased a project's IRR for plants of up to 20 MW (electric), while benefits from increasing plant size were leveling-off for larger plants. However, novel small- to medium-scale commercially proven integrated biomass gasification combined cycle (IGCC) or organic Rankine cycle technology [32] might cancel out gains from economies-of-scale. Plant capacity might need to be driven to a larger extend by proximity to markets for heating or cooling as well as land availability rather than economies-of-scale.

Key factors for a bioenergy growth market are access to financing, long-term feed-in contracts and local heat sales. To make wood-based power production investments competitive in Sub-Saharan Africa research should further focus on i) integrated sustainability assessment methods [18] that consider land-access and -use disputes reduce assessment costs and increase acceptance, ii) improved energy life cycle analysis [16,22] including indirect fossil-fuel consumption, as well as ii) improved understanding of region-specific species and site management including long-term soil productivity and harvest productivities.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2012.11.027.

REFERENCES

[1] UNECA/UNEP. Making Africa's power sector sustainable. An analysis of power sector reform in Africa. Addis Ababa, Ethiopia: United Nations Economic Commission for Africa; 2007 Sep. p. 151.
[2] IEA/UNDP/UNIDO. Energy poverty how to make modern energy access universal? Special early excerpt of the world energy outlook 2010 for the UN general assembly on the millennium development goals. Paris: International Energy Agency; 2010. p. 40.
[3] Buchholz T, Volk T, Tennigkeit T, Da Silva I. Electricity production from energy forests: results from a feasibility and impact scoping study in northern Uganda for a 50 MWe grid model. In: Maniatis K, editor. Proceedings 15th European biomass conference, 7–11 May 2007, Berlin, Germany. Florence: ETA; 2007. p. 2667–71.
[4] FAO Country Profiles [data base on the Internet] Rome – Italy: Food and Agriculture Organization of the United Nations 2012. [cited 2012 Sep 30] Select a country, Uganda; Available from: http://www.fao.org/countryprofiles/default/en/Files updated annually.
[5] The Electricity Access Database [data base on the Internet] Paris – France: International Energy Agency (IEA) – [cited 2012 Sep 30] Available from: http://www.worldenergyoutlook.org/media/weowebsite/energydevelopment/WEO2011_new_Electricity_access_Database.xls Files updated annually.
[6] Banerjee R. Comparison of options for distributed generation in India. Energ Policy 2006;34(1):101–11.
[7] Buchholz T, Da Silva I. Potential of distributed wood-based biopower systems serving basic electricity needs in rural Uganda. Energ Sus Dev 2010;14(1):56–61.
[8] Buchholz T, Volk T, editors. Final report BIOSYRCA project – designing short-rotation coppice bioenergy systems for rural communities in East Africa. Washington DC, USA: United States Agency for International Development [Report on the Internet] [cited 2012 Sep 30]. Available from: pdf.usaid.gov/pdf_docs/PNADL582.pdf; 2007.
[9] Buchholz T, Da Silva I, Furtado J. Power from wood gasifiers in Uganda: a 250 and 10 kW case study. P Civil Eng 2012:165.
[10] Couto L, Nicholas I, Wright L. Short rotation Eucalypt plantations for energy in Brazil, vol. 43. Paris: International Energy Agency (IEA) Bioenergy Task; 2011. p. 17.
[11] Stape JL, Binkley D, Ryan MG, Fonseca S, Loos RA, Takahashi EN, et al. The Brazil Eucalyptus Potential Productivity Project: influence of water, nutrients and stand uniformity on wood production. For Ecol Manag 2010;259(9):1684–94.
[12] Roedl A. Production and energetic utilization of wood from short rotation coppice—a life cycle assessment. Int J Life Cycle Ass 2010;15:567–78.
[13] Heller MC, Keoleian GA, Volk TA. Life cycle assessment of a willow bioenergy cropping system. Biomass Bioenerg 2003;25:147–65.
[14] Heller MC, Keoleian GA, Mann MK, Volk TA. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renew Energ 2004;29(7):1023–42.
[15] Pimentel D, Herz M, Glickstein M, Zimmerman M, Allen R, Becker K, et al. Renewable energy: current and potential issues. Bioscience 2002;52:1111–9.
[16] Zanchi G, Frieden D, Pucker P, Bird N, Buchholz T, Windhorst K. Climate benefits of biomass plantations for energy in Uganda. Biomass Bioenergy, in press.
[17] Amezaga JM, von Maltitz G, Boyes SL. Assessing the sustainability of bioenergy projects in developing countries: a framework for policy evaluation. Newcastle University, ISBN 978-9937-8219-1-9; 2010. p. 179.
[18] Buchholz T, Rametsteiner E, Volk T, Luzadis VA. Multi criteria analysis for bioenergy systems assessments. Energ Policy 2009;37(2):484–95.
[19] van den Broek R, van Wijk A, Turkenburg W. Electricity from energy crops in different settings – a country comparison between Nicaragua, Ireland and the Netherlands. Biomass Bioenerg 2002;22(2):79–98.
[20] Sims REH, Venturi P. All-year-round harvesting of short rotation coppice Eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems. Biomass Bioenerg 2004;26:27–37.
[21] PowerForest v1.0 (Beta) – An energy forest business model for sub-Saharan Africa. Newcastle – UK: Centre for Land Use and Water Resources, [cited 2012 Sept 30]. Available from: http://research.ncl.ac.uk/reimpact/economics2.htm.
[22] Patzek TW, Pimentel D. Thermodynamics of energy production from biomass. Crit Rev Plant Sci 2005;24(5–6):327–64.
[23] Afzal MT, Bedane AH, Sokhansanj S, Mahmood W. Storage of comminuted and uncomminuted forest biomass and its effect on fuel quality. BioResources 2010;5(1):55–69.

[24] Sims REH, Senelwa K, Maiava T, Bullock BT. Eucalyptus species for biomass energy in New Zealand – I: growth screening trials at first harvest. Biomass Bioenerg 1999;16: 199–205.
[25] Sims REH, Maiava TG, Bullock BT. Short rotation coppice tree species selection for woody biomass production in New Zealand. Biomass Bioenerg 2001;20:329–35.
[26] Tolosana E, Laina R, Ambrosio Y. Eucalyptus short rotation woody crops for energy: a literature and experiences review with special reference to industrial trials in Spain. In: Gil L, Tadesse W, Tolosana E, López R, editors. Eucalyptus species management, history, status and trends in Ethiopia. Proceedings from the Congress held in Addis Ababa; September 15th–17th, 2010. p. 370–80.
[27] Buchholz T, Volk TA. Improving the profitability of willow crops – identifying opportunities with a crop budget model. BioEnerg Res 2011;4(2):85–96.
[28] Alder D, Drichi P, Elungat E. Yields of Eucalyptus and Caribbean Pine in Uganda. Consultancy report for the Uganda Forest Resources Management and Conservation Programme, Kampala, Uganda: 2003, p. 52.
[29] Sievers J. The economics of heat storage in CHP plants and integration techniques such as use of buildings as 'batteries' and heat pumps. Proceedings of the DESIRE Seminar, University of Birmingham. University of Kassel; 2005. p. 14.
[30] Everett R, Billington I. Low-cost biomass electricity: more wires or more traffic? Proceedings of the ICE - Energy 2008; 161(1):31–6.
[31] Brown D, Gassner M, Fuchino T, Maréchal F. Thermo-economic analysis for the optimal conceptual design of biomass gasification energy conversion systems. Appl Therm Eng 2009;29(11–12):2137–52.
[32] Brandin J, Tunér M, Odenbrand I. Small scale gasification: gas engine CHP for biofuels. Lund: Swedish Energy Agency; 2011. p. 137.
[33] Buchholz T, Volk TA. Is project scale the key to sustainable modern bioenergy systems in the tropics? J Sustain For 2012; 31:154–73.
[34] Forest Trends Association. State of forest carbon markets 2011: from canopy to currency. Washington DC, USA: Ecosystem Marketplace and Forest Trends Association; 2011. p. 93.
[35] Generation tariffs – Bagasse plants. [data base on the Internet] Kampala – Uganda: Electricity Regulatory Authority – [cited 2012 Sep 30] Available from: http://www.era.or.ug/BaggaseTariffs.php Files updated regularly.

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