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Power from wood gasifiers in Uganda: a 250 kW and 10 kW case study

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Wood gasification systems have the potential to contribute to rural electrification in sub-Saharan Africa. This paper presents an operational and economic analysis of two wood-based gasification systems (250 kW and 10 kW) installed in Uganda in 2007. Both systems proved their potential to compete economically with diesel-generated electricity when operating close to the rated capacity. At an output of 150 kW running for approximately 12 h/day and 8 kW running for approximately 8 h/day, the systems produced electricity at US$0·18 and 0·34/kWh, respectively. A stable electricity demand close to the rated capacity proved to be a challenge for both systems. Fuelwood costs accounted for approximately US$0·03 kWh for both systems. Recovery of even a small fraction of the excess heat (22%) already resulted in substantial profitability gains for the 250 kW system. Results indicate that replicating successful wood gasification systems stipulates the integration of sustainable fuelwood supply and viable business models.

1. Introduction

1.1 Electricity access and human wellbeing

Electricity access is crucial to attain the Millennium Development Goals on poverty reduction and environmental sustainability (OECD/IEA, 2010). Of the 77% of Ugandans living in rural areas in 2008 (FAO, 2011), fewer than 9% had access to electricity (IEA, 2011). Erratic electricity services force industries to spend approximately 34% of total investment into generator back-up systems (Eberhardt *et al*., 2005). Surprisingly, absent modern energy services are not necessarily caused by poverty. Many poor already pay more per unit of energy than the better off due to inefficient technology and corruption (DFID, 2002).

1.2 Electricity from small-scale gasification in Uganda

Despite encouraging biomass productivity conditions, modern bioenergy systems are scarce in Uganda. Established small-scale technology such as gasification can be locally operated providing cost-efficient energy (Buchholz and Volk, 2012; DFID, 2002). Wood-fuelled gasifiers combust biomass in an oxygen-controlled environment, generating producer-gas containing 19 ± 3% carbon monoxide, 10 ± 3% carbon dioxide, 50% nitrogen, 18 ± 2% hydrogen and less than 3% methane (Ankur Scientific India, 2012), which then fuels an internal combustion engine. Wood-based electricity production is characterised by low material and energy input (Heller *et al*., 2004; Pimentel *et al*., 2002; Zanchi *et al*., 2012) and can deliver electricity more cost efficiently than alternatives (Banerjee, 2006; Buchholz and Da Silva, 2010). However, implementation hurdles can be substantial (Ghosh *et al*., 2006) because of its complexity. Systems from 10 kW to 50 MW are under investigation region wide (Buchholz and Volk, 2012; Buchholz *et al*., 2007a, 2007b, 2012; Pamoja Cleantech AB, 2012), and frameworks to mitigate potential ecological and social risks of these systems are being developed (Buchholz *et al*., 2009).

This study investigated the operational and financial implications of a 250 and 10 kW gasifier in Uganda. Visited in 2007, both systems spearheaded the implementation of this technology in East Africa, with the 250 kW unit being the largest system installed to date in sub-Saharan Africa. Revisiting these systems in 2012 reconfirmed their promise and pioneering character.

2. 250 kW gasifcation system

2.1 Background

2.1.1 Muzizi Tea Estate

The Muzizi Tea Estate was visited in January 2007 (Buchholz and Volk, 2007) when it was the property of James Finlay Uganda (2007). James Finlay Uganda consisted of five tea estates totalling over 3000 ha and was Uganda's largest single producer of black tea at the time. The estate is located in Kibaale District, western Uganda. It comprises 371 ha under tea (*Camellia sinensis*) and 99 ha under eucalyptus (*Eucalyptus grandis*). The estate produced 1200 t of black tea in 2006 and employs approximately 400 tea pluckers and 70 factory workers (Figure 1).

2.1.2 Electricity and heat supply and demand before gasifier installation

In 2007, the off-grid estate relied on two 200 kW and one 100 kW diesel generators for its electricity. The factory processes demanded peak loads of 170 kW to run fans reducing the initial moisture content of the daily tea harvest. Processing machinery (conveyor belts, crushers, drier blowers, etc.) required another 180 kW. Assuming an average demand of 260 kW with a 40% load factor over the year, the annual fuel expenses were approximately US\$189 000 or US\$0·16/kg tea produced (considering a 2007 bulk diesel price of US\$0·63/l excluding road tax). Fuelwood from 90 ha of dedicated plantations delivers process heat to dry the tea. The air-dried wood (approximately 15% moisture) is combusted in a boiler generating steam with an estimated 70% efficiency. The fuelwood consumption is approximately 1 kg of air-dried wood (containing approximately 15% moisture) per kilogram of processed tea. Assuming a plantation productivity of 15 oven-dry t/ha per year (odt; containing 0% moisture), approximately 70 ha of plantations are required for a sustainable fuel supply (Section 4).

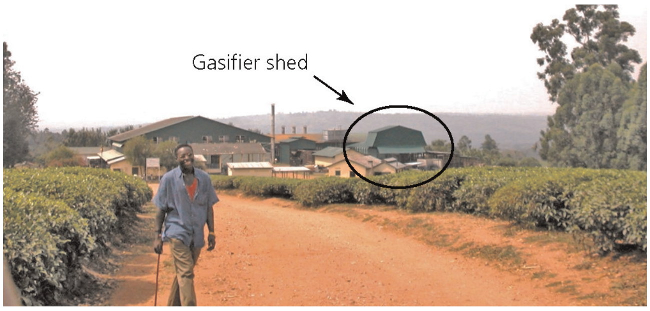

Figure 1. Muzizi Tea Estate processing facility with gasifier shed

2.2 System design

In May 2006, a 250 kW gasifier system was installed at Muzizi Tea Estate, replacing one of the 200 kW diesel generators as a pilot project to investigate its economic competitiveness. The system had been running consistently between August 2006 and the time of the visit in February 2007 on a daily basis for 5·5–6 h.

2.2.1 Fuelwood logistics chain

Fuelwood in 1 m sections and at a moisture content above 40% was delivered to the plant gate (see Section 4 for fuelwood plantation management). The wood was stacked manually and air-dried within 6 months (uncovered) to a moisture content of approximately 15%. In January 2007, wood stacks contained approximately 850 odt, expected to last approximately 6 months for boiler and gasifier. Total fuelwood costs including establishment, maintenance, harvest, transport and stacking were approximately US\$22/odt. Before gasification, fuelwood was cut into 10 × 10 × 10 cm billets on a daily basis with a 15 kW Posch firewood processor containing a circular saw and a hydraulic splitter.

2.2.2 Gasifier and electricity production system

The system included a WBG 400/GAS 250 from Ankur Scientific, India, rated at a gas flow of 1000 $\mathrm{Nm^3/h}$, thermal output of 1200 kWh/h and a biomass consumption of 320–400 kg (air-dried)/h (Ankur Scientific India, 2012), an electric conversion efficiency of 16–20% and a 220 kW net electricity output (Figures 2, 3 and 4). Installed in a 11 × 24 m shed, the system contained

- downdraft gasifier reactor (400 kW thermal output) with automated fuelwood feeder and water-flushed ash and charcoal removal
- cyclone filter separating ash
- producer-gas water-cooling and scrubbing unit containing approximately 20 $\mathrm{m^3}$ water
- two parallel filter units with a coarse filter (wood chips) and two fine filters (sawdust) each to allow switching filter units
- one cloth bag filter
- blower
- three-phase 250 kW Cummins India producer-gas engine with generator
- heat recovery units at the engine's exhaust pipes and the engine's water cooling cycle, connected to the tea drier.

2.2.3 Electricity production and distribution

Started by a 100 kW diesel generator, the system required 30 kW to run pumps, blower, fuelwood feeder, control units

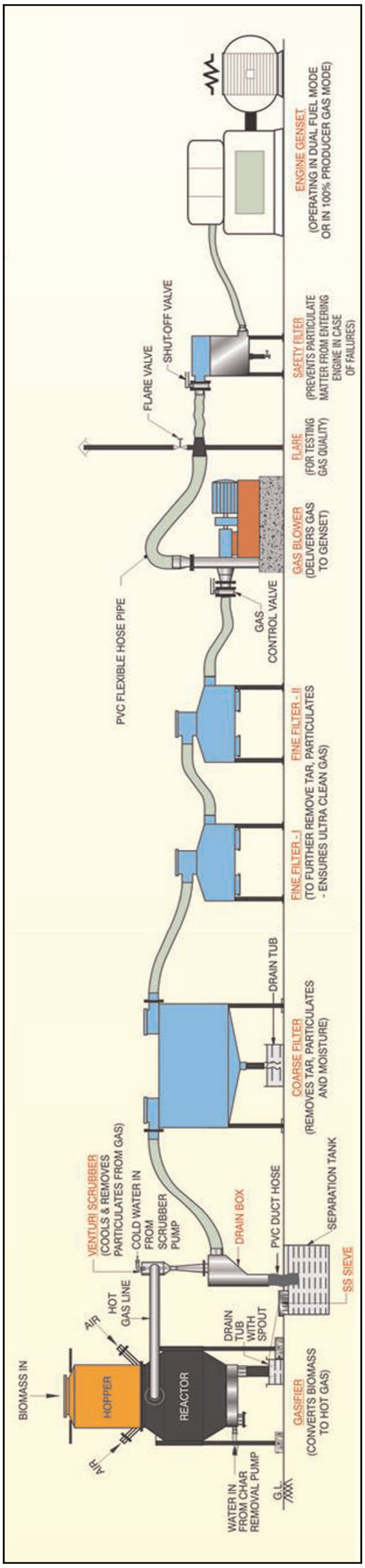

Figure 2. Process flow diagram for Ankur gasification process (reproduced by kind permission of Ankur Scientific, India)

Figure 3. The filter line and WBG 400 gasifier at Muzizi Tea Estate

and so on. Start-up time (cold) was about 7 min. The system ran for approximately 12 h/day continuously, supplying electricity to the withering troughs with high short-term demand variations between 50 and 170 kW.

2.3 System operations

2.3.1 Electricity and heat output

Operations were analysed during 41 days from 12 December 2006 to 23 January 2007 when the system ran 47·7% of the time (Table 1) and was offline 1 day per week for maintenance. Average power output was highly variable with a mean and peak output of 87 kW and 175 kW, respectively (Figure 5).

Figure 4. 250 kW producer-gas engine with heat exchangers (upper left corner at exhaust pipe, heat exchanger at cooling cycle covered by control units) at Muzizi Tea Estate

System parameter	Units	2007 scenario	Improved scenario
Installed electric capacity	kW	250	250
Internal electricity demand	kW	35	35
Internal electricity source		Diesel generator	Gasifier system
Depreciation period	Years	13	13
Average electric output	kW	87	150
Average load factor		47·7%	47·7%
Fuelwood consumption	odt/MWh	1·37	1·37
Fuelwood consumption	odt/year	469	637
Electrical conversion efficiency		14%	14%
Heat recovery rate		22%	22%
Gross electricity production	MWh/year	363	618
Litres of diesel saved	l/year	71 382	149 277
Avoided carbon dioxide emissions[a]	t/year	468	771
Financial parameter			
Alternative electricity cost (diesel derived)	US$/kWh	0·22	0·22
Total capital costs[b]	US$	459 198	442 198
Capital costs per kW installed	US$/kW	2087	2010
Operational costs[c]	US$/year	48 030	31 175
Labour costs[d]	US$/year	17 275	17 497
Fuelwood price[e]	US$/odt	22·0	22·0
Fuelwood costs	US$/kWh	0·03	0·03
Internal rate of return		13%	11%
Payback period	Years	n/a	8
Electricity production costs	US$/kWh	0·29	0·18
Diesel costs saved	US$/year	44 773	93 631

[a] Including avoided carbon dioxide emissions from reducing diesel and fuelwood (tea drying) consumption
[b] Feasibility study; 30 kW diesel generator; civil works; gasifier; engine; shipping; duty, insurance, clearance; fuelwood processor; installation and commissioning; additional electricity controls; training
[c] Land costs, fuelwood, fuel for generator, supplies, wood hauling from stacks, periodical system overhauls
[d] 50% Engineer; skilled assistant; four unskilled assistants; six wood splitters; 40% indirect labour costs
[e] At plant gate

Table 1. 250 kW gasification system installed at Muzizi Tea Estate

The average fuelwood consumption was 1·61 t (air-dried; 15% moisture) or 1·37 odt/MWh electricity produced. Assuming 5·28 MWh/odt (19 GJ/odt; Blunk *et al.*, 2005) energy content for eucalyptus wood, this equalled a gross electrical conversion efficiency of 14% and an extrapolated gross annual electricity output of 363 MWh.

Maximum heat recovery was approximately 80% of the engine exhaust heat (H. Back, 2007, personal communication). Assuming a 33% electric conversion efficiency of the engine, the total heat recovery rate equalled 22% of the original energy content in the fuelwood, offsetting approximately 15% of the fuelwood or 150 odt/year at the boiler.

Several obstacles were diagnosed as a root cause of the low average power output of 87 kW.

- Missing control units: the gasifier system was not able to produce the rated 250 kW but only 150 kW on a constant basis. Lacking control and monitoring units measuring gas pressure, gas composition, air leakage or temperatures prevented a diagnosis.

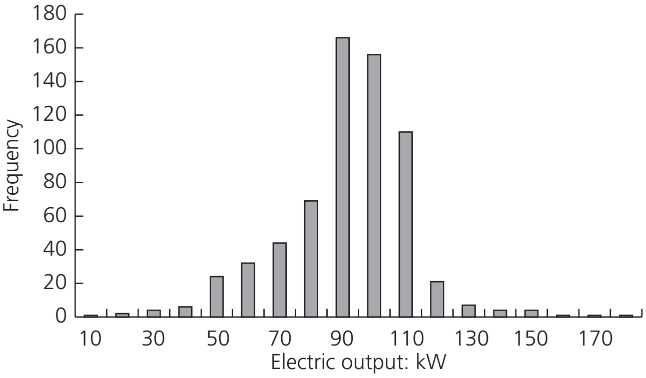

Figure 5. Electric output distribution of the gasifier system over the 41-day period analysed. Measurements were taken every 45 min during operation

- Low electricity demand: the electricity demand averaged only 87 kW output as the gasifier system was only connected to the withering troughs with a low average load. Ideally, the gasifier system should provide a stable base load producing at its maximum capacity and efficiency.
- Volatile electricity demand: the withering troughs were characterised by a highly variable load (load surges of >5 kW within 2 min). Sudden and extreme load changes resulted in gas pressure drop leading to a shut down of the producer-gas engine. Ideally, the gasifier system would provide a stable base load while peak loads were served by diesel generators.
- System diagnosis: frequent shut downs and operating the gasifier far below 150 kW severely restricted the time that was available for analysis of the system internal technical malfunctions.

2.3.2 Financial analysis

Capital costs were US$2087/kW (Appendix 1). At 87 kW output and a load factor of 47·7%, total electricity production costs were US$0·29/kWh (Table 1) compared to diesel-generated electricity costs of US$0·22/kWh. Diesel costs for the internal electricity supply were responsible for 54% of the operating costs (Figure 6). Fuelwood costs equalled approximately US$0·03/kWh of electricity produced. Even the relatively low heat recovery (only 22% of the total wood energy content) saved a total of US$3307 of fuelwood costs at the boiler per year by offsetting approximately 15% of its fuelwood requirements. All electricity costs in US$/kwh are calculated as levelised costs of energy – that is, including all accruing costs over a project's lifetime.

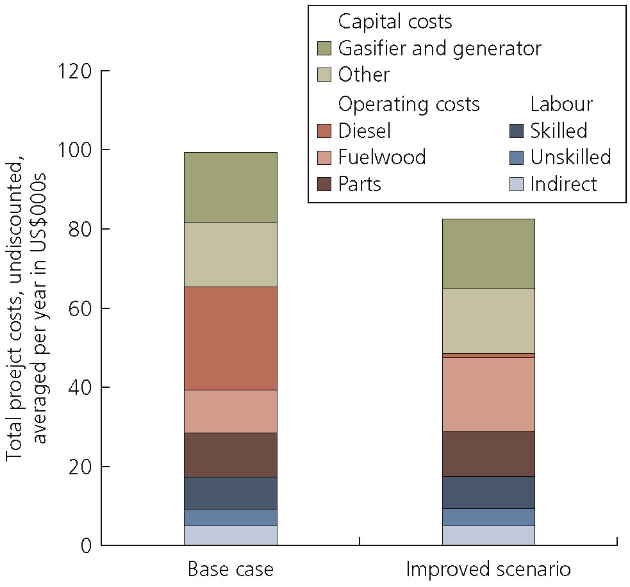

Figure 6. Annualised production costs for the current (87 kW) and improved (150 kW) power output scenario

2.3.3 Employment generation

Excluding the fuelwood supply chain beyond the plant gate, 11·5 full-time jobs were created employing two skilled and four unskilled employees. In early 2007, the estate engineer spent approximately 50% of his time at the gasifier. The fuelwood feeder had to be filled about every 20 min with approximately 60 kg (air-dry) wood. Other work included charcoal and sludge removal, filter cleaning and system monitoring. Another six employees (two shifts of three employees) split wood into billets.

2.3.4 Environmental impacts at the plant

2.3.4.1 ATMOSPHERIC EMISSIONS

Atmospheric emissions from the system were not monitored. Running at an average capacity of 87 kW, the system offset approximately 70 350 litres diesel or 190 t carbon dioxide annually (internal diesel-derived internal electricity demand considered). The heat recovery unit reduced biogenic carbon dioxide emissions at the tea drying boiler by approximately 271 t carbon dioxide/year. Land use-related carbon dioxide fluxes were not included in this estimate.

2.3.4.2 HYDROLOGICAL IMPACTS

The water from the cooling and scrubbing unit (20 m^3) contained ash and charcoal was discharged monthly. As it did not meet standards for discharge into water bodies, waste water was pumped into the tea fields intended to serve as fertilizer. To assess potential long-term environmental impacts of this practice, it would be important to measure pH, biologically hazardous components such as bacteria (unlikely in the case of gasifier waste water), nitrate and other chemical components such as heavy metals or organic carbon compounds, particularly benzene and dioxine contents. A closed waste water cycle as originally designed was not implemented for unknown reasons.

2.4 Improved scenario: increased output to 150 kW

A stable power demand of at least 150 kW would result in increased material and cost efficiencies.

- Diesel costs accounted for over 50% of the operating costs of the system running at 87 kW. Instead, the internal electricity needs could be satisfied with gasifier-generated power resulting in the replacement of the 30 kW diesel generator with a low-cost unit providing sufficient output during start-up only. Serving internal electricity needs from the gasification system itself decreased total project costs by 18% for a 150 kW system compared to the 87 kW scenario (Figure 6).
- While the overall investment costs would remain stable and operating costs would decrease in the 150 kW scenario, the electricity output would increase disproportionately compared to slightly increased labour costs (Table 2). The electricity production costs would decrease from US\$0·29 to 0·18/kWh, resulting in an internal rate of return (IRR) of 11% and a payback period of 8 years (Appendices 2 and 3).
- The increased heat output recovered at the engine would reduce the fuelwood consumption at the boiler for the tea drying process by 20% instead of 15%, saving over US\$4000/year in fuelwood costs at the boiler.

These gains in efficiency and profitability were within reach at Muzizi Tea Estate. The analysis did not consider other optimisation efforts such as increasing the load from 47·7%, improving heat recovery (e.g. recovering heat at the gasifier), and increasing electrical conversion efficiency from 15%. Increasing the power output to 180 kW, the load factor to 60%, the heat recovery rate to 34%, and the overall electric conversion efficiency to 16% (1·2 odt/MWh) resulted in electricity production costs of US\$0·11/kWh, an IRR of 48%, and a payback period of 4 years. This scenario would produce electricity at 50% of the costs of 2007 diesel-derived alternatives. In addition, systems of this size might qualify for the carbon dioxide offset market. At a price of US\$5/t carbon dioxide of avoided diesel-derived carbon dioxide emissions, the improved scenario would be able to generate an additional US\$2000/year (excluding carbon dioxide emissions related to land use).

3. Mukono 10 kW gasification system

3.1 Background and system design

As of February 2007, the system was installed on a 100 acre farm in Mukono, Uganda, producing pork and aloe vera and was financed by Deutscher Entwicklungsdienst. It included a downdraft gasifier WBG 15 from Ankur Scientific, India, rated with a gas flow of 37·5 Nm^3/h, a thermal output of 45 kWh/h, and a biomass consumption of 12–15 kg (air-dried)/h (Ankur Scientific India, 2012). It was fuelled by *Eucalyptus* ssp. prunings from the farm with diameters greater than 2 cm. Twigs were air-dried for 3 months and cut with a circular saw to a length of 5 cm. A 12·5 kW Fieldmarshall modified diesel engine produced three-phase electricity (<10 kW) running on dual-fuel mode with a minimum of 25% diesel by energy content. The system was started by a car battery on 100% diesel. The producer-gas was filtered through a water scrubber, sawdust and cloth filter. The fuel mix was regulated automatically by the engine speed. Starting time was between 5 and 10 min. The footprint was 4 × 4 m with another 10 × 4 m shed for storage and processing of the woodfuel (Figures 7 and 8). The water cycle for cooling and filtering contained 500 litres of water. The grid consisted of 30 electricity poles and 700 m of wire connecting the farm house, pig sty and security lights.

3.2 System operations

3.2.1 Electricity output and efficiency

The gasification system had been running stable between August 2006 and February 2007 on a daily basis for 5·5–6 h in the evenings, producing 3.55 kW on one phase (15 amp, 230–240 V). The system was operated by an employee with a degree in electrical installations at a workload of approximately 1·5 h/day for maintenance and 3 h/day for fuelwood preparation. The pond water was replaced every 2–3 months.

Parameter	Units	Sample	National standards for effluent discharge
PH		6·02	6·0–8·0
Electrical conductivity	μS/cm	3570	1500
Colour	PtCo	88 800	500
Turbidity	NTU	3896	300
Total suspended solids	mg/l	23 600	100

Table 2. Waste water sample August 2006 for 250 kW system (James Finlay Uganda, 2007)

Figure 7. Gasifier shed with fuelwood storage and processing shed attached

Producing 20·4 kWh/day (5·75 h or a load factor of 24% with a 3·55 kW output), the gasification system used 3·17 kg of air-dried wood and 0·18 litres diesel kWh electricity produced (Table 3). The diesel to fuelwood ratio was close to 1 : 1 in contrast to the 1 : 3 ratio rated by the manufacturer. The overall electricity conversion rate was 6% or 3% for fuelwood only. Compared with a diesel-powered alternative, the system saved only 3·2 litres diesel/day. Lacking control units made it difficult to monitor the system.

3.2.2 Financial analysis

Electricity production costs were compared to a diesel-powered alternative of comparable capacity, load and grid system as it was installed before the gasification system. A 3·55 kW diesel generator running for 5·75 h/day at a 2007 diesel price of US$0·94/l (including road tax) produced electricity at US$0·56/kWh. Assuming a 10 kW diesel generator running at 3.55 kW would increase costs to US$0·74/kWh (see Appendix 4).

As the system was running in 2007, it produced electricity at US$0·78/kWh (Table 3). Diesel fuel accounted for 22% of total annualised costs (Figure 9). Costs for fuelwood (20 odt/year) did not occur.

3.3 Increasing load while decreasing diesel demand

The main obstacles to resource and cost-efficient system operation for the 10 kW unit were the small load (5·75 h/day at 36% of the rated capacity) and the high diesel share (54% by energy content) with the latter probably caused by running the system well below its rated capacity.

Plans at Mukono Farm were to extend the grid to a nearby village to increase power demand. In this improved scenario, an increased average power output (8 kW) was assumed resulting in an increased fuelwood to diesel ratio of 3 : 1, and increased grid and labour costs (Table 3). A daily operation of 8 h with 2 days per month offline (31% load) was assumed. A formalised business model was evaluated including fuelwood costs (US$22/odt) and the purchase of road tax-exempt diesel (US$0·69/l). This scenario would produce electricity at US$0·34/kWh (US$0·03/kWh for fuelwood), which would be comparable to diesel-derived electricity production costs (US$0·39/kWh).

Figure 8. 10 kW dual-fuel mode gasifier for electricity production

This improved scenario reflects typical equipment requirements and load for a Ugandan rural settlement (Furtado, 2012) to the best knowledge of the authors. While the dual-fuel system offers benefits in terms of reduced carbon dioxide emissions and reliance on fossil fuels, the dual-fuel system provides only marginal economic advantages compared to the diesel-fuelled alternative, even under ideal conditions. As diesel fuel costs still accounted for 17% of total costs of the dual-fuel system (Figure 9), a system running 100% on fuelwood such as sold by All Power Labs (2012) under the same conditions (8 kW, 31% load) was also considered. With slightly increased capital costs (Table 3), the analysis suggests that a 100% wood-fuelled system would be able to produce electricity at US$0·31/kWh, reducing electricity production costs by over 20% compared to a diesel-fuelled system of comparable scale (35% if road taxed diesel is used).

4. Sustainable fuelwood supply

4.1 Achieving sustainable fuelwood supply in East Africa

Viable gasification systems hinge on a year-round reliable biomass in terms of quantity and quality. Abundant and concentrated biomass ‘waste’ is by and large a myth in East Africa where agro-industries are sparse and agricultural residues play an essential role in the agriculture’s nutrient cycle (Giller *et al.*, 2009). Bagasse, maize cobs, nut shells, rice or coffee husks might be of limited availability at small-scale central processing plants

System parameter	Units	2007 scenario	Improved scenario	100% wood
Installed electric capacity	kW	10	10	10
System start-up		Car battery	Car battery	Car battery
Depreciation period	Years	10	10	10
Average electric capacity	kW	3·55	8	8
Average daily use		24%	31%	31%
Fuelwood share in fuel mix		46%	75%	100%
Fuelwood consumption	kg/kWh (air dry)	3·73	1·73	2·19
Diesel consumption	l/kWh	0·18	0·08	0
Electrical conversion efficiency	wood only/fuel mix	3%/6%	11%/13%	12%/n/a
Gross electricity production	kWh/year	7451	21 900	21 900
Fuelwood consumption	odt/year	17	23	29
Litres of diesel saved per day[a]	l/day	3·2	15.1	20
Avoided carbon dioxide emissions[b]	t/year	3·1	14·9	19·7
Financial parameter				
Capital costs[c]	US$/kW	2250	2625	2890
Alternative electricity cost (diesel derived)[d]	US$/kWh*	0·56	0·39	0·39
Fuelwood priced	US$/odt	0	22	22
2007 diesel priced	US$/l	0·94	0·69	0·69
Fuel costs (wood and diesel)	US$/kWh	0·17	0·08	0·03
Electricity production costs	US$/kWh	0·78	0·34	0·31
Diesel costs saved	US$/year	1097	3801	5037

[a] Compared to diesel-generated power supply
[b] Diesel-derived carbon dioxide emissions only, changes in land use-derived carbon dioxide fluxes not considered
[c] Including capital costs for grid installation
[d] Scenarios differ in their inclusion of road tax, load factor and installed capacity
[e] Improved and 100% wood scenario assume a formalised business model including price points for biomass

Table 3. 10 kW System installed at Mukono Farm

but seasonality and fuel quality (e.g. moisture or ash content) restrict its use. Short rotation woody crops (SRWC) can be grown and harvested all year on sites too marginal for food production (Hoogwijk *et al.*, 2005) such as steep slopes, degraded land or agricultural fallows (Siriri and Raussen, 2003), and can result in improved site conditions. SRWC systems consist of densely planted trees or shrubs that are harvested at 1–4 year intervals and resprout after harvest (coppice; Figure 10). While maintaining a high productivity such as the native *Markhamia lutea*, or *Eucalyptus* ssp., SRWC systems produce many environmental and rural development benefits such as soil conservation, biodiversity enhancement and carbon sequestration (Aronsson *et al.*, 2000; Heller *et al.*, 2003; Tolbert *et al.*, 2002; Volk *et al.*, 2004).

4.2 Area demand for biomass production

A gasification system running 100% on producer-gas with an electrical conversion efficiency of 10–20%, a 50% load would require 1–2 ha/kW or 3·3–6·7 km/kW of hedgerows assuming a low site productivity (5 odt/ha per year; Table 4). For the improved scenario at Muzizi Tea Estate (150 kW, 47% load, 14% electrical conversion efficiency) with a productivity of 15 odt/ha per year, the gasification system would require 42 ha of dedicated fuelwood plantations. The improved scenario at Mukono Farm (25% diesel share in fuel mix, 8 kW, 31% load, 11% electrical conversion efficiency), 2·9 ha of fuelwood plantations or 9·7 km of hedgerows would be required at a productivity of 15 odt/ha per year. These acreages do not yet account for supply buffers, transport and storage losses, or large-scale plantation infrastructure such as roads and firelines (Buchholz *et al.*, 2012).

In the case of Muzizi Tea Estate, fuelwood demand for tea drying and the gasifier is covered by 99 ha of company-owned *Eucalyptus grandis* plantations in plot sizes of 2–8 ha (Figure 11). Seventy hectares are already required to satisfy

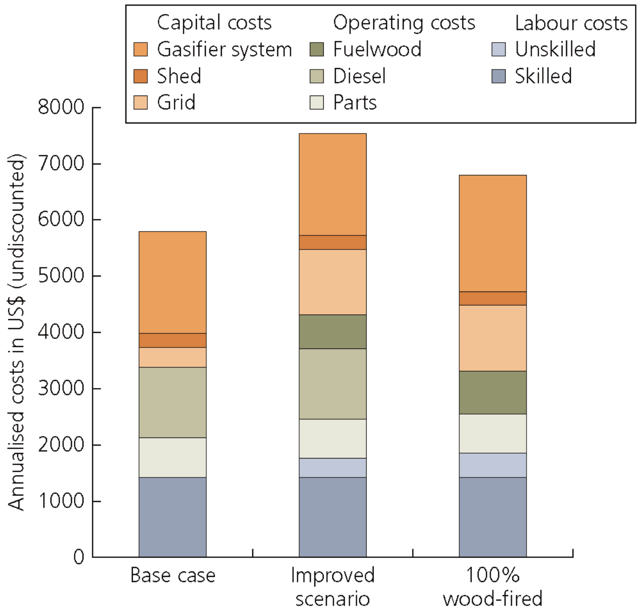

Figure 9. Annualised production costs for the 10 kW base case and alternative scenarios

Figure 10. Eucalyptus coppice 1·5 years after cutting

fuelwood needs for the tea drying process. Trees are planted at densities of 1300–2200 trees/ha. Establishment included site clearing, contact herbicide application (1·5 l/ha glyphosate), planting and a total of six to eight manual weedings per stand every 4–8 weeks in the wet or dry season, respectively. Stands were replanted after harvesting. Since May 2006, coppice regrowth is being tested (Figure 10). Post-establishment maintenance is restricted to yearly stand inventories and pest monitoring. Mean annual increment ranged from 10 to 40 odt/ha per year (J. Sandom, 2007, personal communication) with a mean of 15 odt/ha per year. In 2006, 15 ha aged 7–11 years were harvested with a mean diameter at breast height of 17–20 cm. Harvest and transport operations include manual underbrush removal, felling by chainsaw, debranching with machetes, 1 m bucking by chainsaw, manually splitting and moving sections to roadside from where sections are transported by truck for 0·7–2 km to the tea factory.

4.3 Environmental, economic and social considerations and the dynamic aspect of a sustainable fuelwood supply

The fuelwood supply is the most challenging bioenergy component when assessing its sustainability. Competing demands for fertile land (e.g. food production) or the long-term impact on soil quality of SRWC systems (Patzek and Pimentel, 2005) deserve scrutiny. Long-term viability of 15 odt/ha per year productivities as reported at Muzizi Tea Estate are challenged

Stand productivity: odt/ha per year	10% Electric conversion efficiency[b]				20% Electric conversion efficiency[c]			
	50% Load[d]		70% Load[e]		50% Load[d]		70% Load[e]	
5	2·0	(6·7)	2·8	(9·3)	1·0	(3·3)	1·4	(4·7)
10	1·0	(3·3)	1·4	(4·7)	0·5	(1·7)	0·7	(2·3)
15	0·7	(2·2)	0·9	(3·1)	0·3	(1·1)	0·5	(1·6)
20	0·5	(1·7)	0·7	(2·3)	0·2	(0·8)	0·3	(1·2)

[a] 3 m hedge width
[b] 2·68 air or 2·28 oven-dried kg/kWh (assuming 19 GJ/odt)
[c] 1·34 air or 1·14 oven-dried kg/kWh
[d] 12 h/day at full capacity
[e] 16·8 h/day at full capacity

Table 4. Fuelwood plantation requirements in ha/kW (hedgerows[a] in km/kW)

Figure 11. Harvest and transport operations in a 7-year-old *Eucalyptus grandis* stand at Muzizi Tea Estate; coppicing stumps in right-hand foreground

by much lower long-term productivities (approximately 3 odt/ha per year) of natural forests in East Africa (Pimental *et al.*, 2002).

The resilience of a fuelwood supply system rests on its capacity to react to changing climates, pathogens or market conditions. A diversification of SRWC species can reduce the severity of natural hazards. Reducing reliance on herbicides (e.g. by using termite-resitant species such as *Markhamia lutea*) or mineral fertilizer (e.g. by using nitrogen-fixing species such as *Acacia* ssp. or the native *Sesbania sesban*) can limit exposure to volatile fossil-fuel markets (Heller *et al.*, 2003).

4.4 Small compared with large-scale systems

Economies of scale are realised by reducing capital costs for the 10 kW compared to the 250 kW system (US$2890 and US$2010/kW, respectively), resulting in lower production costs (US$0·18 and US$0·31/kWh, respectively). However, scale analysis supersedes economics as scale is a crucial factor in determining a gasifier's impact on its surroundings (Buchholz and Volk, 2012). A 3 kW system could be fuelled by tree trimmings, agricultural residues, hedgerows or woodlots planted on slopes between adjacent fields. A 10 kW system might already necessitate up to 31 km of hedgerows at a productivity of 15 odt/ha per year. The 250 kW at Muzizi Tea Estate requires a more coordinated approach to ensure continuous and sustainable biomass supply. Large-scale systems might create electricity demands beyond the basic needs typical for rural villages that in themselves can challenge sustainability perceptions and are more likely to trigger unintended consequences such as increased electricity demand and increased competition for biomass (Naughton-Treves *et al.*, 2007).

4.5 Fuelwood business models

Fuelwood business models have to provide incentives for suppliers to deliver sustainably sourced biomass all year. This can be achieved either by vertically integrating the fuelwood supply chain into the entity running the gasifier system, or by outgrower schemes in which the electricity producer supports fuelwood providers such as farmers to grow and sell fuelwood from woodlots or agroforestry systems. Outgrower systems require focused extension services covering training, quality monitoring and provision of material to growers.

Given the high operational costs of small diesel-based electricity production, biomass-based alternatives are particularly competitive. Paying premiums for sustainably sourced fuelwood does not erode this cost advantage. For the improved 10 kW scenarios, fuelwood costs contributed only 7% to total electricity costs or US$0·03/kWh. More than doubling fuelwood prices from US$22 to US$50/odt would not nullify the competitive advantage of gasifiers towards diesel-based alternatives.

A vertically integrated fuelwood supply might not be required or face major implementation challenges (e.g. due to the lack of capital) for smaller systems. In the case of an outgrower scheme, competition with food production, biodiversity, site protection or forest health would have to be addressed. In the case of dedicated fuelwood plantations managed professionally, advanced silvicultural models providing multiple products such as mixed timber–fuelwood plantations might become commonplace.

5. Status of case studies in 2012

Both systems investigated were decommissioned in early 2012. At Muzizi Tea Estate, the national grid extended its service to the site at $0·12–0·16/kWh (Umeme Limited, 2012) rendering onsite power production uncompetitive. The Mukono Farm system was decommissioned in 2008 when the farmer left the area.

Between early 2007 and spring 2012, road diesel prices in Uganda rose by nearly 30% from US$0·96 to US$1·31/l while other cost factors remained fairly stable. Revisiting the 2007 scenarios, the improved scenario at Muzizi Tea Estate (150 kW at 47·7% load) would have produced an IRR of 33% instead of 11% and a payback period of 4 years instead of 8 years considering April 2012 diesel prices. For the Mukono Farm system, a 100% fuelwood-based gasifier producing 8 kWh at a 31% load would undercut April 2012 diesel-derived electricity costs by 60%, yielding a cost of electricity of US$0·31 instead of 0·52/kWh.

6. Conclusions

6.1 Viable as internal power source

Gasification can out-compete diesel-generated electricity in East Africa. The 250 kW system and the 10 kW dual-fuel system produced electricity at rates (US$0·29/kWh at 87 kW and approximately 50% daily load and US$0·78/kWh at 3.55 kW and 24% daily load, respectively) close to 2007 diesel-derived electricity production (US$0·22 and US$0·56/kWh, respectively) for comparable scales. Gasification systems provide some additional logistical challenges in conjunction with the increased labour requirements (time and expertise) compared to alternative electricity production systems (Buchholz and Da Silva, 2010). However, labour costs played a minor role in the overall production costs. Absent stable and sufficient power demands rendered both systems uncompetitive with diesel-based systems. Increasing output to 150 kW at Muzizi Tea Estate under unchanged load resulted in US$0·18/kWh electricity costs, IRR of 11% and payback of 8 years. Increasing the output to 8 kW, the 10 kW system was competitive under a minimum load of 30%, which corresponds to typical loads for a rural village in Uganda (Buchholz and Volk, 2012; Furtado, 2012), and producing electricity at US$0·34/kWh. Adding more control units to standard gasification systems could greatly improve system performance in the short run by improving and expanding existing datasets for further research.

6.2 Success factors and challenges

6.2.1 Success factors

- Serving internal electricity needs, both systems eliminated administrative and operational burdens when selling electricity to potentially multiple and external customers.
- Sufficient fuelwood sources were present including fuelwood management expertise in the case of Muzizi. Using wood as fuel can eliminate competition with food production by relying on marginal land.
- There was a committed management willing to pioneer an untested technology regionally.
- Muzizi Tea Estate was able to secure funds through its mother company interested in multiplying the system in case of success. Mukono Farm received financing through a donor agency.
- There was practical expertise to operate gasifiers. Muzizi Tea Estate received international engineering assistance.

6.6.2 Challenges

- Missing stable and sufficient demand, both systems performed below the rated capacity causing economic and mechanical challenges.
- Mukono Farm had limited means to monitor the wood–diesel mix, resulting in inadequate diagnosis of how to reduce costly diesel consumption. At Muzizi Tea Estate, missing control units prevented analysis of the quantity and quality of producer-gas.
- Corrosion threatened long-term viability of the gasifier and filter systems.

6.3 Sustainability and fuelwood supply

Fuelwood systems need to accommodate the scale and environment of the operation. While larger systems could rely on dedicated SRWC plantations, outgrower schemes with agroforestry components such as hedgerows can serve smaller units. In particular, smaller units have the capacity to pay adequate fuelwood prices ensuring sustainability standards without becoming uncompetitive. A fuelwood price of US$22/odt equalled US$ 0·03/kWh for fuelwood. Land availability might be a more vital factor than fuelwood price. At a load of 50%, systems with a 20% electrical conversion efficiency would require 0·5 ha/kW or 1·7 km hedgerows/kW assuming site productivities of 10 odt/ha per year.

6.4 Viable business models

These results and other research (Buchholz *et al.*, 2012; Tennigkeit *et al.*, 2006) demonstrate the competitiveness and the challenge when generating electricity with biomass gasification systems. Viable business models need to synchronise the system's capacity to the power demand. Electricity consumers might be overburdened by this task lying outside of their core business. The creation of energy service companies (Ellegård *et al.*, 2004; Lee *et al.*, 2003; Vine, 2005) could mitigate this situation. Commercialising heat recovery can further increase profits at limited costs. Furthermore, long-term feed-in tariffs are crucial to spur the installation of the costly technology (>US$2000/kW).

Extending services to multiple customers adds further complexities. New off-grid electricity production models based on gasification are being created by, for example, Husk Power Systems in India or by Pamoja in Uganda (Pamoja Cleantech AB, 2012). In these cases, anchor loads and long-term tariffs are secured through providing electricity to telecommunication towers while excess electricity is sold to rural communities. This structure allows professional management – avoiding managerial pitfalls typical of rural electrification efforts (Ghosh *et al.*, 2006; Nouni *et al.*, 2007; Ravindranath *et al.*, 2004). In general, all three components of bioenergy – feedstock supply, conversion technology and energy allocation – need to be integrated with local involvement to produce truly sustainable energy at an appropriate scale (Buchholz *et al.*, 2009).

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Appendix 1. Cash flow for gasifier at 87 kW (base case scenario)

Project year	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Capital costs														**459 198**
Feasibility study	40 000													40 000
Diesel generator 30 kW	21 000													21 000
Building (including water pool)	30 000													30 000
Gasifier	99 651													99 651
Syngas generator	129 547													129 547
Shipping	10 000													10 000
Duty, insurance, clearance	10 000													10 000
Fuelwood processor	30 000													30 000
Wood processing shed	5000													5000
Installation and commissioning	40 000	20 000												60 000
Additional electricity controls	20 000													20 000
Training (Andrew to India)	4000													4000
Operating costs														**624 212**
Land costs[a]	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Fuelwood[b]	10 864	10 864	10 864	10 864	10 864	10 864	10 864	10 864	10 864	10 864	10 864	10 864	10 864	141 232
Diesel for genset	25 947	25 947	25 947	25 947	25 947	25 947	25 947	25 947	25 947	25 947	25 947	25 947	25 947	337 310
Maintenance material	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6001	78 001
Maintenance diesel generator	420	420	420	420	420	420	420	420	420	420	420	420	420	5460
Wood hauling from stacks	1323	1323	1323	1323	1323	1323	1323	1323	1323	1323	1323	1323	1323	17 193
Top-up engine overhaul		5000				5000				5000				15 000
Major overhaul				10 000				10 000				10 000		30 000
Labour costs														**224 569**
Engineer	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	88 136
Assistant, skilled	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	17 627
2 assistants, unskilled	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	17 627
Indirect labour costs 40%	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	64 163
Wood splitters	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	37 017
Revenues														**1 028 011**
Electricity	75 770	75 770	75 770	75 770	75 770	75 770	75 770	75 770	75 770	75 770	75 770	75 770	75 770	985 012
Heat (offset fuelwood costs at boiler)	3308	3308	3308	3308	3308	3308	3308	3308	3308	3308	3308	3308	3308	42 999
Total revenues	79 078	79 078	79 078	79 078	79 078	79 078	79 078	79 078	79 078	79 078	79 078	79 078	79 078	**1 028 011**
Total costs	501 027	86 829	61 829	71 829	61 829	66 829	61 829	71 829	61 829	66 829	61 829	71 829	61 830	**1 307 979**
Gross margin	−421 949	−7751	17 249	7249	17 249	12 249	17 249	7249	17 249	12 249	17 249	7249	17 248	**−279 968**
Accumulated CF	−421 949	−429 701	−412 452	−405 204	−387 955	−375 707	−358 458	−351 210	−333 961	−321 713	−304 464	−297 216	−279 968	**−4 679 959**
Present value	−421 949	−7047	14 255	5446	11 781	7605	9736	3720	8047	5195	6650	2541	5496	**−348 526**

[a] 'Land costs' include costs for the area covered by the shed and the wood stacks

[b] Fuelwood costs are 'at plant gate' including all forest operations, land lease and transport

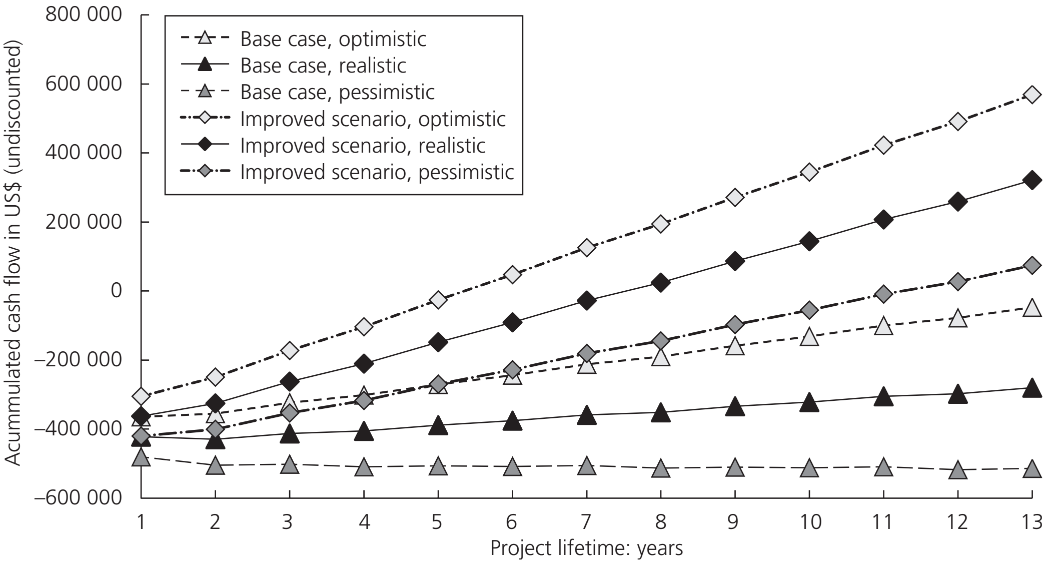
Appendix 2. Cash flow for gasifier at 150 kW (improved scenario)

Project year	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Capital costs														**442 198**
Feasibility study	40 000													40 000
Diesel generator 30 kW	4000													4 000
Building (including water pool)	30 000													30 000
Gasifier	99 651													99 651
Syngas generator	129 547													129 547
Shipping	10 000													10 000
Duty, insurance, clearance	10 000													10 000
Fuelwood processor	30 000													30 000
Wood processing shed	5000													5000
Installation and commissioning	40 000	20 000												60 000
Additional electricity controls	20 000													20 000
Training (Andrew to India)	4000													4000
Operating costs														**403 421**
Land costs[a]	1	1	1	1	1	1	1	1	1	1	1	1	1	19
Fuelwood[b]	18 731	18 731	18 731	18 731	18 731	18 731	18 731	18 731	18 731	18 731	18 731	18 731	18 731	243 503
Diesel for genset	963	963	963	963	963	963	963	963	963	963	963	963	963	12 522
Maintenance material	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6001	78 001
Maintenance diesel generator	80	80	80	80	80	80	80	80	80	80	80	80	80	1040
Wood hauling from stacks	1795	1795	1795	1795	1795	1795	1795	1795	1795	1795	1795	1795	1795	23 336
Top-up engine overhaul		5000				5000				5000				15 000
Major overhaul				10 000				10 000				10 000		30 000
Labour costs														**227 456**
Engineer	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	6780	88 136
Assistant, skilled	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	17 627
2 assistants, unskilled	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356	17 627
Indirect labour costs 40%	5760	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	4936	64 987
Wood splitters	4909	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	2847	39 079
Revenues														**1 395 320**
Electricity	102 843	102 843	102 843	102 843	102 843	102 843	102 843	102 843	102 843	102 843	102 843	102 843	102 843	1 336 957
Heat (offset fuelwood costs at boiler)	4489	4489	4489	4489	4489	4489	4489	4489	4489	4489	4489	4489	4489	58 363
Total revenues	107 332	107 332	107 332	107 332	107 332	107 332	107 332	107 332	107 332	107 332	107 332	107 332	107 332	**1 395 320**
Total costs	469 930	69 845	44 845	54 845	44 845	49 845	44 845	54 845	44 845	49 845	44 845	54 845	44 846	**1 073 076**
Gross margin	−362 598	37 487	62 487	52 487	62 487	57 487	62 487	52 487	62 487	57 487	62 487	52 487	62 486	**322 244**
Accumulated CF	−362 598	−325 111	−262 624	−210 137	−147 650	−90 163	−27 676	24 810	87 297	144 784	207 271	259 758	322 244	**−379 795**
Present value	−362 598	34 079	51 642	39 434	42 679	35 695	35 272	26 934	29 151	24 380	24 091	18 396	19 910	**19 066**

[a] 'Land costs' include costs for the area covered by the shed and the wood stacks

[b] Fuelwood costs are 'at plant gate' including all forest operations, land lease and transport

Appendix 3. Accumulated cash flow at base case (87 kW) and improved (150 kW) power output scenario



Appendix 4. Cash flow for the 10 kW gasifier installed at Mukono (3·55 kW output, 5·75 h/day)

Project year	1	2	3	4	5	6	7	8	9	10	Total
Capital costs											
Gasifier and diesel engine	20 650										**20 650**
Shed	2500										**2500**
Operating costs											
Parts	700	700	700	700	700	700	700	700	700	700	**7000**
Fuelwood	897	897	897	897	897	897	897	897	897	897	**8975**
Diesel	1	1	1	1	1	1	1	1	1	1	**5**
Skilled labour (electrician FTE.5)	1424	1424	1424	1424	1424	1424	1424	1424	1424	1424	**14 237**
Unskilled labour	430	430	430	430	430	430	430	430	430	430	**4304**
Grid	5751	657	657	657	657	657	657	657	657	657	**11 663**
Revenues	**8621**	**8621**	**8621**	**8621**	**8621**	**8621**	**8621**	**8621**	**8621**	**8621**	**86 212**
Total costs	**32 353**	**4109**	**4109**	**4109**	**4109**	**4109**	**4109**	**4109**	**4109**	**4109**	**69 334**
Gross margin	**−23 732**	**4512**	**4512**	**4512**	**4512**	**4512**	**4512**	**4512**	**4512**	**4512**	**16 878**
Accumulated CF	**−23 732**	**−19 220**	**−14 707**	**−10 195**	**−5683**	**−1171**	**3341**	**7854**	**12 366**	**16 878**	**−34 270**
Present value	**−23 732**	**4102**	**3729**	**3390**	**3082**	**2802**	**2547**	**2315**	**2105**	**1914**	**2254**