ELECTRICITY FROM WOOD-FIRED GASIFICATION IN UGANDA – A 250 AND 10KW CASE STUDY

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ABSTRACT

Wood gasification systems have the potential to contribute to the rural electrification in Sub-Saharan Africa. This paper presents an operational and economic analysis of two wood-based gasification systems (250 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 ~12 h/day and 8 kW running for ~8h/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 ~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 integration of sustainable fuelwood supply and viable business models.

Keywords: Small-scale gasification, economic and operational analysis, sustainable fuelwood supply

1 INTRODUCTION

1.1 ELECTRICITY ACCESS AND HUMAN WELL-BEING

Electricity access is crucial to attain the Millennium Development Goals on poverty reduction and environmental sustainability [1]. About 77% of Ugandans live in rural areas [2]. In 2008, only 4% of the rural population had access to electricity [2]. Unreliable or absent electricity services forces industries to invest an estimated 34% of total investment into generators as backup systems [4]. Surprisingly, the absence of basic modern energy services is not necessarily a result of financial poverty. Many poor already pay more per unit of energy than the better off due to inefficient technology and corruption [5].

1.2 ELECTRICITY FROM SMALL-SCALE GASIFICATION IN UGANDA – TWO CASE STUDIES

Despite encouraging biomass growth conditions, modern bioenergy systems have been largely neglected in Uganda. Proven small-scale conversion technology like gasification can be operated by locally trained personnel and provides efficient and low-carbon energy at the local level [5, 6]. Gasifiers running on air-dried wood (moisture content <20%) combust biomass in a controlled oxygen environment generating producer-gas containing 19±3% CO, 10±3% CO_2, 50% N_2, 18±2% H_2, and up to 3% CH_4[7]. The producer-gas fires an internal combustion engine producing electricity. Wood-based electricity production is characterized by low material and energy input [8][9][10] and has the potential to deliver electricity more cost-efficiently than other electricity sources [2][12], but implementation hurdles can be substantial [13] due to its complexity. Plants ranging from 10 kW to 50 MW are being investigated across the region [14][15][16][17][18]. Concurrently, decision frameworks to mitigate potential negative ecological and social impacts of these systems are being developed [19].

We investigated operational and financial implications of a 250 kW and a 10 kW gasifier in Uganda. Both systems were visited in 2007 when they spearheaded the implementation of such systems in East Africa. The 250 kW unit is the largest system installed to date in Sub-Saharan Africa. Revisiting these systems in 2011 reconfirmed their promise and pioneering character.

2 MUZIZI TEA ESTATE 250 KW GASIFCATION SYSTEM

2.1 BACKGROUND

2.1.1 Muzizi Tea Estate

The Muzizi Tea Estate was visited in January 2007 [14] when it was property of James Finlay Uganda (JFU) which was a subsidiary of John Swire & Sons Ltd, UK. JFU comprised five tea estates totaling over 3,000 ha and was Uganda's largest single producer of black tea at the time, growing and processing over 10,000 tons annually. In previous years, JFU was responsible for over a quarter of Uganda's tea exports.

Figure 1: Muzizi Tea Estate processing facility with gasifier shed.

The Muzizi Tea 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 1,200 tons of black tea in 2006 and employs around 400 tea pluckers and 70 factory workers. The tea is auctioned in Mombasa, Kenya, where mean prices achieved in 2006 were around US$1.50/kg.

2.1.2 Electricity and heat supply and demand prior to gasifier installation

In 2007, the estate had no connection to the national grid and relied on two 200 kW and one 100 kW diesel generators for electricity. Excluding domestic and office use, the factory processes required an installed capacity to meet peak loads of 170 kW. This was used to run fans circulating air in the withering troughs, where the moisture content of the daily tea harvest is reduced by 70% within 12 hours. 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 ~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 is combusted in a boiler, generating steam at an estimated 70% efficiency. The tea is dried at a temperature of ~80° C. The fuelwood consumption is ~1 kg of air-dried wood per kg of processed tea. Assuming a plantation productivity of 15 oven-dry t/ha/yr (odt; containing 0% moisture), ~70 ha of plantations are required to assure a sustainable fuel supply (section 4).

2.2 SYSTEM DESIGN

In May 2006, JFU installed a 250 kW gasifier system at the Muzizi Tea Estate, replacing one of the 200 kW diesel generators in order to reduce costs. In case of success, such systems would be considered for other company-owned off-grid tea estates as well. Pre-commissioning activities were carried out in 2005. The system had been running consistently between August 2006 and the time of visit in February 2007.

2.2.1 Fuelwood logistics chain

Fuelwood with a moisture content above 40% arrives at the plant gate on trucks cut and split to 1 m sections (section 4). The wood is stacked manually and air-dried (uncovered) to ~15% moisture content within 6 months. In January 2007, there was a total of ~850 odt wood stored, expected to last ~6 months for boiler and gasifier. Harvest, transport, and wood stacking was outsourced for ~US$13/odt. Total fuelwood costs including establishment, maintenance, harvest, transport, and stacking were estimated at US$22/odt, equaling the price paid to farmers who occasionally sell fuelwood to the plant. Prior to gasification, fuelwood was cut into 10x10x10 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 contained the WBG 400/GAS 250 from Ankur Scientific, India, rated at a gas flow of 1,000 Nm^3/h, a thermal output of 1,200 kWh/h, and a biomass consumption of 320-400 kg(air-dried)/h [7], equaling an electric conversion efficiency of 16-20%. It is rated at 220 kW net electricity output. Installed in a shed measuring 11x24 m (excluding wood storage and water cooling pond), the system included (Figure 2):

- 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 ~20 m^3 water.
- Two parallel filter units with a coarse filter (wood chips) and two fine filters (sawdust) each to allow constant operations during cleaning of one filter system.
- One cloth bag filter.
- Blower transferring producer-gas to the engine.
- Three-phase 250 kW Cummins India producer-gas engine.
- Heat recovery units at the engine's exhaust pipes and the water cooling cycle, connected to the tea drier.

2.2.3 Electricity production and distribution

A 100 kW diesel generator started the gasifier system, delivering 30 kW required to run the system (pumps, blower, fuelwood feeder, control units, etc.). Start-up time was about 7 min when cold. The system ran for approximately 12 h/day continuously, supplying electricity to the withering troughs whose demand ranged from 50 to 170 kW with high short-term variations.

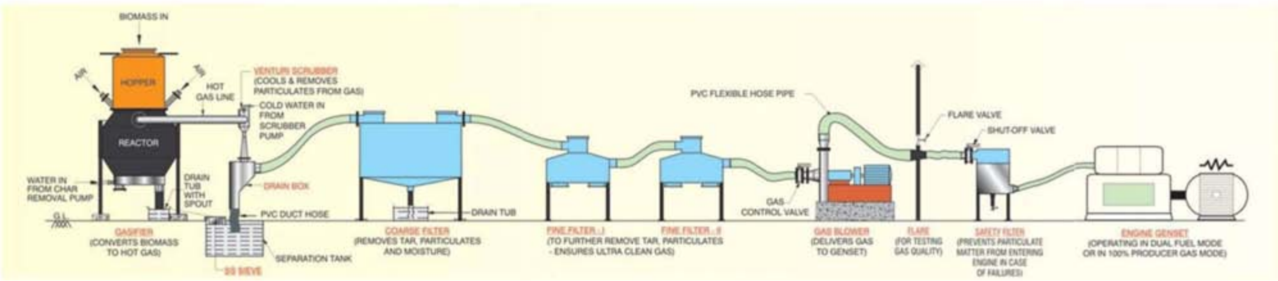

Figure 2: Process flow diagram for Ankur gasification process [7].

Figure 3: Filter line and WBG 400 gasifier.

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).

2.3 SYSTEM OPERATIONS

2.3.1 Electricity and heat output

The dataset analyzed covered 41 days from December 12 2006 to January 23 2007. During this time period, the system was running 47.7% of the time (Table 1) and was offline one 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), far below the rated 250 kW peak capacity.

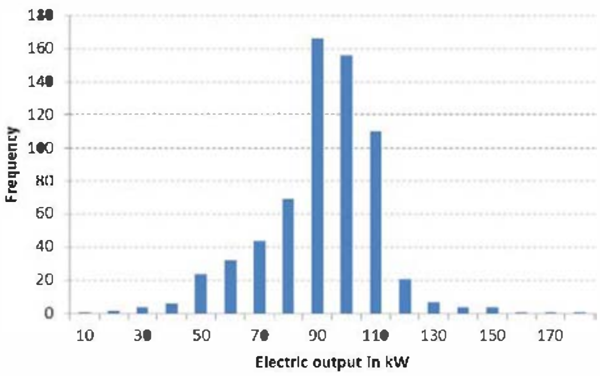

Figure 5: Electric output distribution of the gasifier system over the 41 day period analyzed. Measurements were taken every 45 min during operation.

The diesel generator providing system-internal 30 kW demand and an estimated average 5 kw for the fuelwood processor consumed around 41,357 l/yr.

The average fuelwood consumption was 1.61 t (air-dried; 15% moisture) or 1.37 odt/MWh electricity produced. Considering an energy content of 5.28 MWh/odt (19 GJ/odt) of Eucalyptus wood, this equals a gross electrical conversion efficiency of 14%. Extrapolating this dataset, the total gross annual electricity output equaled 363 MWh.

Maximum heat recovery was ~ 80% of the engine exhaust-heat [20]. Assuming a 33% electric conversion efficiency of the engine, the total heat recovery rate equaled 22% of the original energy content in the fuelwood, offsetting around 15% of the fuelwood or 150 odt/yr at the boiler.

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

- **Low electricity demand:** Although the gasifier system was able to produce 150 kW on a constant base, the low average 87 kW output was due to a design problem in the electrical system as the gasifier system was only connected to the withering troughs with an average load below 150 kW. Ideally, the gasifier system should provide a stable base load producing at its maximum capacity and efficiency.
- **Volatile electricity demand:** The withering troughs are characterized by a highly variable load (defined here as changes in power demand of >5 kW within 2 min). Switching one trough out of 34 off resulted in a load drop of 10 kW. Variable loads result in gas pressure change not synchronized with the producer-gas engine leading to a shut down. Ideally, the gasifier system would provide a stable base load while peak loads served by diesel generators.
- **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.
- **System diagnosis**: Frequent shutdowns 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$2,087/kW (see Appendix 2). At 87 kW output and a load factor of 47.7%, total electricity production costs wereUS$0.29/kWh (Table 1) which was considerably higher than diesel-generated electricity (US$0.22/kWh based on a bulk purchase price of US$0.63/l for non-road diesel). All electricity costs in US$/kwh are calculated as levelized costs of energy, i.e. including all accruing costs over a project's lifetime. Operating costs represented the highest total cost share; diesel costs for the internal electricity supply were responsible for 54% of the operating costs (Figure 6).

Table 1: System performance and financial analysis of gasification system installed at Muzizi Tea Estate.

System parameter	Unit	2007 scenario	Improved scenario
Installed electric capacity	kW	250	250
Internal electricity demand	kW	35	35
Internal electricity source		Diesel	Gasifier
Depreciation period	years	13	13
Average electric capacity	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 eff.		14%	14%
Heat recovery rate		22%	22%
Gross electricity prod.	MWh/year	363	618
Liters diesel saved /year	l/year	71,382	149,277
Avoided CO_2emissions[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/ kW installed	US$/kW	2,087	2,010
Operational costs[c]	US$/year	48,030	31,175
Labor costs[d]	US$/year	17,275	17,497
Fuelwood price[e]	US$/odt	22.0	22.0
Fuelwood costs	US$/kWh	0.03	0.03
IRR		-13%	11%
Payback period	years	n/a	8
Electricity production costs	US$/kWh	0.29	0.18
Diesel costs saved	US$/year	44,773	93,631

[a]) Including avoided CO_2 emissions from avoided use of diesel at the generator and fuelwood for the tea drying process.
[b]) Capital costs include: feasibility study; 30 kW diesel generator for internal power needs; building (including water pool); gasifier; gas engine; shipping; duty, insurance, clearance; fuelwood processor; wood processing shed; installation and commissioning; additional electricity controls; and training.
[c]) Operational (non-labor) costs include: land costs, fuelwood, fuel for generator, maintenance material, wood hauling from stacks, top up engine overhaul every five years and major overhaul every four years.
[d]) Labor costs include costs of: 50% engineer; skilled assistant; four unskilled assistants and six wood splitters; indirect labor costs of 40% are included. [e]) Fuelwood costs at plant gate, including all occurring costs such as land lease, operations, transport.

At a fuelwood price of US$22/odt, fuelwood costs equaled ~US$0.03/kWh of electricity produced at a 15% conversion efficiency. Even the low heat recovery (only 22% of total energy content wood) improved the IRR from -16% to -13%, saving a total of US$3,307 of fuelwood costs at the boiler per year by offsetting ~15% of its fuelwood requirements. Savings other than fuelwood at the boiler (labor, operating costs, potentially downgrading size of boiler with reduced capital costs) were not considered in this conservative estimate.

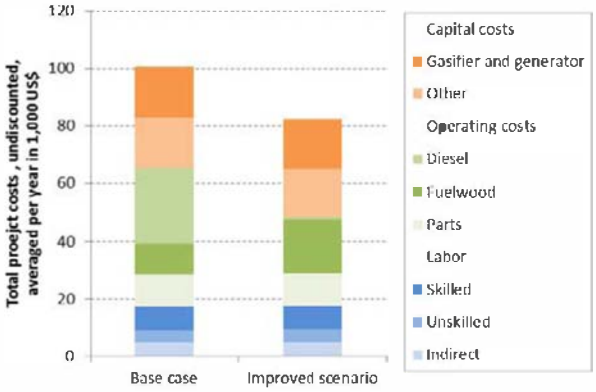

Figure 6: Annualized production costs for the current (87 kW) and improved (150 kW) power output scenario.

2.3.3 Employment generation

11.5 full-time jobs (excluding fuelwood supply chain beyond the plant gate) were created employing two skilled (one engineer with a BS degree and an assistant) and four unskilled employees (two shifts @ two employees). At the time of the visit, the estate engineer spent ~50% of his time at the gasifier. The fuelwood feeder had to be filled about every 20 min with ~60 kg (air-dry) wood. Other work included charcoal and sludge removal, filter cleaning, and system monitoring. Another 6 employees (two shifts @ three employees) split wood into billets.

2.3.4 Environmental impacts at the plant

Atmospheric emissions

Specific air emissions from the system were not monitored. The system, as it was running in 2007 at 87 kW, offset around 70,350 l diesel or 190 t CO_2/yr (diesel-derived CO_2 emissions originating in system-internal power demand included). Additionally, the heat recovery unit reduced biogenic CO_2 emissions at the tea drying boiler by an estimate of 271 t CO_2/yr. Land-use related CO_2 fluxes are not included in this estimate.

Hydrological impacts

The waste water from the cooling and scrubbing unit (20m^3) contained ash and charcoal from the gasification process and was discharged once per month. The waste water quality did not meet standards for discharge into water bodies (Table 2). 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 like bacteria (unlikely in the case of gasifier waste water), nitrate (to prevent groundwater pollution), and other chemical components such as heavy metals or organic carbon compounds, particularly benzene and dioxine contents. A closed waste water cycle requiring regular dreging of sludge and topping off water losses as originally designed was not implemented for unknown reasons.

Table 2: Waste water sample from August 2006 with national Ugandan standards for discharge in water bodies [21] which is not practiced at Muzizi Tea Estate.

PARAMETER	UNITS	SAMPLE	NATIONAL STANDARDS FOR EFFLUENT DISCHARGE
pH		6.02	6.0-8.0
Electrical conductivity	µS/cm	3,570	1,500
Color	PtCo	88,800	500
Turbidity	NTU	3,896	300
Total suspended Solids	mg/L	23,600	100

2.4 IMPROVED SCENARIO: INCREASED OUTPUT TO 150 KW

A constant output of 150 kW has been technically proven for the gasification system at Muzizi Tea Estate and was the scenario on which JFU based its purchase decision. A stable power demand of 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. This design would result in the replacement of the 30 kW diesel generator with a low-cost unit that can provide sufficient output during system startup time only (ca. 30 min per start). 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, the electricity output would increase disproportionately compared to slightly increased labor costs (Table 1). The electricity production costs would decrease from US$0.29 to 0.18/kWh, resulting in an IRR of 11% and a payback period of 8 years (Appendix 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$4,000/yr in fuelwood costs at the boiler.

These remarkable gains in efficiency and profitability were within reach at Muzizi Tea Estate and demonstrate the maturity of the system. This analysis did not consider other system optimization 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. Additionally, systems of this size might qualify for the CO_2 offset market. At a price of US$5/t CO_2 of avoided diesel-derived CO_2 emissions, the improved scenario would be able to generate additional US$2,000/yr (excluding CO_2 emissions related to land use).

3 MUKONO 10 KW GASIFICATION SYSTEM

3.1 BACKGROUND AND SYSTEM DESIGN

The system was visited in February 2007 when it was installed on a 100 acre farm in Mukono, Uganda, producing pork and *Aloe vera*. The gasifier, producer-gas processing units and generator was financed by DeutscherEntwicklungsdienst (DED).

It included a downdraft gasifier WBG 15 from Ankur Scientific, India, rated at a gas flow rate of 37.5 Nm^3/h, a thermal output of 45 kWh/h, and a biomass consumption of 12-15 kg(air-dried)/h [7]. It is fueled by Eucalyptus ssp. prunings from the farm with diameters of less than 2 cm. Twigs are cut by a circular saw to a length of 5 cm and air-dried for 3 months. A 12.5 kW Fieldmarshall modified diesel engine produces three-phase electricity (10 kW max.) running on dual fuel mode with a minimum of 25% diesel by energy content.

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

The system is started by a car battery on 100% diesel. A blower is not required. The producer-gas is filtered through a water scrubber, sawdust, and cloth filter. The fuel mix is regulated automatically by the engine speed. Starting time is between 5 to 10 min. Waste heat is not recovered. The footprint was 4x4 m with another 10x4 m shed for storage and processing of the woodfuel (Figure 7&8). The water cycle for cooling and filtering contained 500 l of water. The grid consisted of 30 electricity poles and 700 m of wire connecting the farm house, pig stay and security lights.

Figure 8: 10 kW dual fuel mode gasifier for electricity production

3.2 SYSTEM OPERATIONS

3.2.1 Electricity output and efficiency

At the time of the visit, the gasification system had been running stable between August 2006 and February 2007 on a daily base 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 three years college degree in electrical installations with a workload of ~1.5 h/day for maintenance and 3 h/day for fuelwood preparation. The pond water was replaced every 2-3 months.

Producing 20.4 kWh/day (5.75hrs or a load factor of 24% with a 3.55 kW output), the gasification system used 55 kg air-dried wood and 3.7 l diesel/day or 3.17 kg of air dried wood and 0.18 l 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 to a diesel-powered alternative, the system saved only 3.2 l diesel/day. Missing control units made it difficult to monitor the unfavorablefuelwood:diesel ratio as well as the electricity conversion rate.

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 prior to 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.

Table 3: System performance and financial analysis of gasification system installed at Mukono farm.

System parameter	**Unit**	**2007 scen.**	**Impr-ovedscen.**	**100% Wood**
Installed electric cap.	kW	10	10	10
System startup		Car battery	Car battery	Car battery
Depreciation period	Years	10	10	10
Avg electric capacity	kW	3.55	8	8
Average daily use		24%	31%	31%
Wood-share of fuel		46%	75%	100%
Wood cons.(air dry)	kg/kWh	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	7,451	21,900	21,900
Fuelwood consumption	odt/year	17	23	29
Liters of diesel saved per day[a]	l/day	3.2	15.1	20
Avoided CO_2emissions[b]	t/year	3.1	14.9	19.7
FINANCIAL PARAMETER				
Capital costs[c]	US$/kW	2,250	2,625	2,890
Alternative electricity cost (diesel-derived)[d]	US$/kWh*	0.56	0.39	0.39
Fuelwood price[e]	US$/odt	0	22	22
Diesel price	US$/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	1,097	3,801	5,037

[a]) Compared to diesel-generated power supply.
[b]) Diesel-derived CO2 emissions only, changes in land-use derived CO2 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 formalized business model including price points for biomass.

As the gasification system was running in 2007, it produced electricity at US$0.78/kWh (Table 3). Diesel fuel accounted for 22% of total annualized costs (Figure

9). Costs for fuelwood (20 odt/yr) were not considered as tree clippings were considered a waste product. Increasing electric conversion efficiency would therefore not be cost-effective under this base-case scenario.

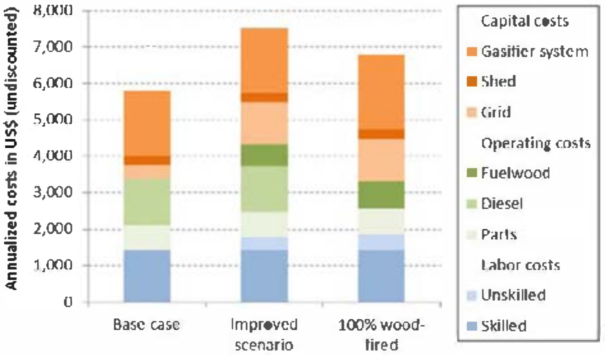

Figure 9: Annualized production costs for the 10 kW base case and alternative scenarios.

3.3 INCREASING LOAD WHILE DECREASING DIESEL DEMAND

The two main obstacles to resource- and cost-efficient electricity production at the Mukono farm were the low daily load (5.75 h/day at 36% of the rated capacity). The high diesel share of 54 % is most likely caused by running the system at only a fraction of the rated.

Plans at Mukono farm were to extend the grid to a nearby village to increase power demand. In this improved scenario, we assumed an increased average power output (8kW) resulting in an increased fuelwood to diesel ratio of 3:1 (as rated by the manufacturer), and increased grid and labor costs (Figure 9). We assumed a daily operation of 8 h with two days per month offline (31% load). We evaluated a formalized business model including fuelwood costs (US$22/odt) and purchase of road-tax exempt diesel (US$0.69/l) as power would be sold past the farm gate. This improved scenario would produce power at US$0.34/kWh, which would be comparable to diesel-derived electricity production costs (US$0.39/kWh). Fuelwood costs were responsible for US$0.03/kWh generated.

This improved scenario reflects typical load- and equipment-related limitations for a project supplying electricity to a rural settlement [22] electrification efforts and described load and the most favorable economic outline for the 10 kW dual fuel system to the best knowledge of the authors. While the dual fuel system offers benefits in terms of reduced CO_2 emissions and reliance on fossil fuels, the gasifier-based system provides only marginal economic advantages compared to diesel-fueled alternative, even under ideal conditions. As diesel fuel costs still accounted for 17% of total costs of the dual fuel system (Figure 9), we also considered a system running 100% on fuelwood such as sold by All Power Labs [22]. With slightly increased capital costs (Table 3), this alternative did not differ from the improved dual fuel system described above in terms of loads and system design. The authors' analysis suggests that a 100% wood-fueled system would be able to produce electricity at US$0.31/kWh, reducing electricity production costs by over 20% compared to a diesel-fueled system of comparable scale (35 % if road-taxed diesel is used).

4 SUSTAINABLE FUELWOOD SUPPLY

4.1 SUSTAINABLE FUELWOOD SUPPLY IN EAST AFRICA

An economically viable gasification system hinges on a feedstock supply that is reliable in quantity and quality throughout the year. The existence of abundant and concentrated biomass 'waste' is by and large a myth – at least in East Africa where agro-industries with their respective waste streams are sparse and agricultural residues play an essential role in the agriculture's nutrient cycle. The sourcing of biomass of sustainable origin is a formidable implementation hurdle to overcome.

Figure 10: Eucalyptus coppice 1.5 years after cutting.

Bagasse, corn cobs, nut shells, rice or coffee husks might be available in limited quantities at small-scale central processing plants but seasonality and fuel quality (e.g. moisture or ash content) restrict its use. Short Rotation Woody Crops (SRWC) can be grown and harvested year-round on low-quality sites that are too marginal for food crop production [24] such as steep slopes, degraded land or agricultural fallows [25], and even resulting in improved site conditions. SRWC systems consist of densely planted trees or shrubs that are harvested at 1-4 yr intervals and resprout after harvest (coppice; Figure 10) while maintaining a high productivity such as the native *Markhamialutea*, or Eucalyptus ssp. SRWC systems produce many environmental and rural development benefits like soil conservation, biodiversity enhancement and carbon sequestration [26][27],[28][29].

4.2 AREA DEMAND FOR BIOMASS PRODUCTION

Assuming a 50 % load and a low site productivity (5 odt/ha/yr), a gasification system running 100% on producer-gas at an electrical conversion efficiency of 10-20% would require 1-2 ha/kW or 3.3-6.7 km/kW of hedgerows (Table 4). Assuming an improved scenario at Muzizi Tea Estate (150 kW, 47% load, 14% electrical conversion efficiency) with a productivity of 15 odt/ha/yr, the gasification system would require 42 ha of dedicated fuelwood plantations. Assuming 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/yr. These area requirements do not yet account for supply buffers, transport and storage losses, or – in the case of large-scale fuelwood plantations – plantation infrastructure such as roads and firelines[18].

As an example for fuelwood plantation management, the Muzizi Tea Estate's 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). 70 ha are already required to satisfy fuelwood needs for the tea drying process. Seedlings of different origin (South Africa, Kenya, Zimbabwe) and grown in an onsite nursery are planted by employees in a 3x2.5 to 2.5x2.5m spacing (1,300 to 2,200 trees/ha). Establishment included site clearing, laying out of planting lines, pitting holes, contact herbicide application (1.5 l/ha glyphosate), planting, and manual weeding every month or second month in the wet or dry season, respectively, totaling 6-10 weedings per stand. Previously, stands were replanted after harvesting. Since May 2006, coppice regrowth is being tested (Figure 10). No maintenance operations are scheduled except for yearly stand inventories and pest monitoring. Mean annual increment (MAI) range from 10 to 40 odt/ha/yr[30] with a mean of 15 odt/ha/yr. In 2006, 15 ha of stands aged 7 to 11 years were harvested with a mean diameter at breast height of 17-20 cm. Harvest and transport operations include manual removal of underbrush, felling trees by chainsaw, debranching with machetes (branches are left on site for fuelwood gatherers), 1 m bucking of stems by chainsaw, manually splitting and moving sections to the roadside where it is hauled on a truck for 0.7-2 km to the tea factory.

4.3 ENVIRONMENT, 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 [19]. Resource requirements such as competing demands for fertile land (e.g. food production) or the long-term impact on soil quality of SRWC systems [31] deserve scrutiny. Long-term viability of productivities of 15 odt/ha/yr as reported at Muzizi Tea Estate are challenged by the considerably lower long-term productivity (~ 3 odt/ha/yr) of natural forests in East Africa [32].

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 severity of natural hazards such as the 2006 outbreak of the chalcid wasp (*Leptocybeinvasa*) which affected *Eucalyptus grandis*stands at Muzizi Tea Estate. Reducing reliance on herbicides (e.g. by using termite-resitant species such as *Markhamialutea)* or mineral fertilizer (e.g. by using nitrogen-fixing species such as Acacia ssp. or the native *Sesbaniasesban*) can limit exposure to volatile fossil-fuel markets [27].

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

4.4 SMALL- VS. LARGE SCALE SYSTEMS

Economies of scale are mainly observed in a reduction of capital costs for the 10 kW vs. 250 kW system (US$2,890 and US$2,010/kw, respectively), resulting in lower production costs (US$0.18 and US$0.31/kWh, respectively). However, scale analysis goes beyond economics as scale is a crucial factor in determining a gasification's system impact on its surroundings [6]. A 3 kW system could be fueled by tree trimmings, residues from small-scale agricultural production, dispersed hedgerows, or small 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/yr. A larger scale system such as installed at Muzizi Tea Estate requires a more coordinated approach to ensure continuous biomass supply and its sustainable production. Large-scale systems might create electricity demands beyond the basic needs typical for rural villages that in itself can challenge conventional sustainability perceptions and are more likely to trigger unintended consequences such as increased electricity demand and subsequently increased competition for biomass [32].

4.5 FUELWOOD SUPPLY BUSINESS MODELS

Business models for a fuelwood supply system have to provide incentives for farmers and entrepreneurs to provide biomass year-around and from sustainable sources. This can be achieved either by direct management of fuelwood sources through the electricity provider or by outgrower schemes which encourage local farmers to grow fuelwood in small lots or in agroforestry systems, eventually selling it to the plant. Outgrower systems require focused extension services covering training, quality monitoring, and provision of material to farmers.

Given the high operational costs of small diesel-based electricity production, biomass-based alternatives are particularly competitive. Even high fuelwood costs do not erode this cost-advantage. For the 10 kW system, fuelwood costs contributed only 7% to total electricity costs or US$0.03/kWh. This cost-advantage allows for investments into a sustainable fuelwood supply. Even increasing fuelwood prices from US$22 to US$50/odt would nullify the competitive advantage of a gasifier towards diesel-based alternatives.

A vertically-integrated fuelwood supply system in which woodlots are owned and managed by the company running the gasifier might not be required or face major implementation challenges (e.g. due to the lack of capital) for smaller systems. In case of an outgrower scheme, competition with food production, biodiversity, site protection, or forest health would have to be addressed. In case of dedicated fuelwood plantations managed professionally, advanced silvicultural models satisfying multiple product demands such as mixed timber-fuelwood plantations might become commonplace.

5 STATUS IN 2011

Both systems were decommissioned as of late 2011. In the case of Muzizi Tea Estate, the electricity grid was extended to the site rendering onsite power production uncompetitive to grid electricity sold at $0.12-0.16/kWh [35]. The Mukono farm system was decommissioned in 2008 when the farmer left the area and the gasifier system was transferred to the engineering department at Makerere University, Kampala.

Since early 2007, road-diesel prices in Uganda rose by nearly 30% from US$0.96 to US$1.22/l while other cost factors remained fairly stable. Revisiting the economics of the 2007 scenarios, the improved scenario at Muzizi Tea Estate (150 kW at 47.7 % load) would have produced a IRR of 27% instead of 11% and a payback period of 5 instead of 8 years considering 2011 diesel prices. In the case of the Mukono farm system, a 100% fuelwood based gasifier producing 8 kWh at a 31% load would undercut 2011 diesel-derived electricity costs by 60%, yielding a cost of electricity of US$0.31 instead of 0.49/kWh).

6 CONCLUSIONS

6.1 Viable as internal power source

Gasification can be an economically attractive alternative to diesel generated electricity in East Africa considering increasing fossil fuel prices. The 250 kW system and the 10 kW dual-fuel system produced electricity at rates (US$0.29/kWh at 87 kW and ~50% daily load and US$0.78/kWh at 3.55 kW and 24% daily load, respectively) close to diesel-derived electricity production in comparable scales (0.22 and US$0.56/kWh, respectively).

The absence of a stable and sufficient power demand hindered both systems to become commercially competitive to fossil-fuel based systems. Increasing output to 150 kW at Muzizi Tea Estate under unchanged load resulted in electricity production costs of US$0.18/kWh, an IRR of 11 % and a payback over 8 years.When 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 [22] and producing electricity at US$0.34/kWh. Gasification systems fueled by 100% wood can produce power for 0.31 US$/kWh at this scale and load. Economies of scale are mainly observed in a reduction of capital costs per kW installed. Fuelwood costs were a considerable factor for the 250 kW unit (23% of total costs or US$0.04/kWh) while negligible under improved scenarios for the 10 kW unit (7% or US$0.03/kWh). The commercial use of excess heat can play a major economic role.

6.2 SUCCESS FACTORS AND CHALLENGES

Success factors

- Both systems were *serving internal electricity needs*, eliminating administrative and operational burdens to sell electricity to potentially multiple customers.
- *Sufficient fuelwood sources were present* as well as management and fuelwood logistics expertise in the case of Muzizi.
- A *committed management* willing to pioneer a technology untested in the region.
- Muzizi Tea Estate was *able to secure funds* through its mother company with the intend to multiply the system in case of success. Mukono farm received financial support from a donor agency.

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

Stand productivity (odt/ha/yr)	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.

- *Practical expertise* to run gasification systems assisted in overcoming operational challenges. Muzizi Tea Estate received advice from international engineers.

Challenges

- Instead of providing a *stable and sufficient demand,* both systems ran below the rated capacity causing economic and mechanical challenges.
- The system at Mukono farms had *limited means to monitor* the wood-diesel mix, resulting in inadequate

options to reduce diesel consumption and therefore production costs. At Muzizi Tea Estate, missing control units prevented a rapid analysis of the quantity and quality of producer-gas flows.
- *Corrosion* threatened long-term viability especially at 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 probably rely on dedicated SRWC plantations, outgrower schemes with agroforestry components such as hedgerows can serve smaller units. Particularly, smaller units have the capacity to pay adequate fuelwood prices ensuring sustainability standards without becoming uncompetitive. A fuelwood price of US$22/odt equaled US$ 0.03/kWh. Land availability to produce fuelwood might be a more vital factor than fuelwood price. At a load of 50%, even systems with a 20% electrical conversion efficiency would require 0.5 ha/kW or 1.7 km hedgerows/kW at sites with a fuelwood productivity of 10 odt/ha/yr.

6.4 VIABLE BUSINESS MODELS

These case studies and other research [18],[34] demonstrate the competitiveness but also the challenge to generate electricity with biomass gasification systems. A viable business model needs to optimize the system's capacity to the power demand. End users might be overburdened by this task. The creation and support of Energy Service Companies [36][36][37] could serve this end. Commercializing heat recovery can greatly enhance a system's profitability at limited additional costs. Long-term feedin-tariffs are crucial to overcome investment risks when installing the costly technology (>US$2,000/kW). Extending services to multiple customers adds further complexity to the task. New off-grid biomass gasification-based electricity production business models are being created by e.g. Husk Power Systems in India [39] or by Pamoja in Uganda [17]. Anchor loads and long-term tariffs are secured through providing electricity to telecommunications towers while excess electricity is sold to rural communities. This unique customer structure allows professional power production management and avoids managerial pitfalls for which rural electrification efforts are known for [13][40]. In general, all three components of bioenergy - feedstock supply, conversion technology and energy allocation - need to be integrated with local involvement to effect change and produce truly sustainable energy at an appropriate scale [19].

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APPENDIX

Appendix 1: 10 yr cash flow for the 10 kW gasifier installed at Mukono (3.55 kW output, 5.75 hr/day).

	total
Gasifier and diesel engine	18,000
Shed	2,500
Parts	7,000
Fuelwood	0
Diesel	12,627
Skilled labor (electrician FTE .5)	14,237
Unskilled labor	0
Grid	3,551
Revenues	41,810
Total costs	57,916
Gross margin	-16,106
Accumulated CF	-187,811
Present Value (PV)	-18,033

Appendix2: Cash flow for gasifier at 87 kW (base case scenario).

	Total
Capital costs	**459,198**
Feasibility study	40,000
Diesel generator 30 kW	21,000
building (including water pool)	30,000
Gasifier	99,651
Syngas generator	129,547
Shipping	10,000
Duty, insurance, clearance	10,000
Fuelwood processor	30,000
Wood processing shed	5,000
Installation and commissioning	60,000
Additional electricity controls	20,000
Training (Andrew to India)	4,000
Operating costs	**624,212**
Land costs*	16
Fuelwood**	141,232
Diesel for genset	337,310
Maintenance material	78,001
Maintenance diesel generator	5,460
Wood hauling from stacks	17,193
Top up engine overhaul	15,000
Major overhaul	30,000
Labor costs	**224,569**
Engineer	88,136
Assistant, skilled	17,627
2 assistants, unskilled	17,627
Indirect labor costs 40%	64,163
Wood splitters	37,017
Revenues	**1,028,011**
Electricity	985,012
Heat (offset fuelwood costs at boiler)	42,999
Total revenues	**1,028,011**
Total costs	**1,307,979**
Gross margin	**-279,968**
Accumulated CF	**-4,679,959**
Present Value (PV)	**-348,526**

* 'Land costs' include costs for the area covered by the shed and the wood stacks

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

Appendix 1: Accumulated cash flow at base case (87 kW) and improved (150 kW) power output scenario at Muizi tea estate.