Biogas in Small Gasoline Gensets

Business opportunities and tests

Project no: 244.WW.001

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1 INTRODUCTION

1.1 Background

Biogas is the product of anaerobic digestion, the biological degradation of biomass in the absence of oxygen. It is mixture of methane and carbon dioxide, with traces of hydrogen, nitrogen and hydrogen sulfide. As a fuel gas, it can be used for a range of applications, including heating (cooking, drying), lighting, power (mechanical and electrical) and refrigeration. The production of biogas can be done at virtually any scale, and with different technologies ranging from (very) simple to (very) complex.

The versatility of biogas, its relative ease of production and the wide availability of suitable feedstocks makes biogas an interesting energy technology for application in developing countries. As such, FACT Foundation has been promoting the technology for years, and has been working on means of investment cost reductions, feedstock availability, gas applications and effluent processing.

One of the issues that FACT is currently working on is finding business opportunities for SME’s , e.g. for producing electricity for battery charging and lighting. Small systems producing household energy have limited earning capacity, while larger systems (>10 kW) require considerable investments that are outside the investing capacity of the typical entrepreneur. A small digester system with a 1-5 kW generator set could be an interesting solution.

Main issue in the development of a business case is the selection of a genset that can be modified to run on biogas; its performance, durability and costs. For this reason, FACT has decided to start a number of trials with a small gasoline generator, and, based on the results, develop a business case for SME’s.

In parallel to this work, FACT has commissioned an entrepreneur in Uganda to conduct a range of real-life trials with a small digester and generator set. The results of this work are expected to become available mid-2013.

1.2 Objectives

The objectives of this work are the following:

1. Determine the requirements for modifying a gasoline genset to run on biogas
2. Assess the performance (power, efficiency, stability) of the genset running on biogas in comparison to other fuels
3. Define a business case for an SME to operate a biogas system and a small genset

2 TRIALS

2.1 Methodology

Although the ultimate goal of the trials was to determine the performance of a gasoline generator set running on biogas, it was decided also to determine its performance on other fuels:

- Gasoline, in order to have a reference for the "normal"operation of the generator set
- LPG, in order to have a reference for a gaseous fuel for which an existing modification kit is commercially available;
- Natural gas, as this is a gas that can be considered inbetween LPG and biogas in terms of calorific value and air requirements

2.1.1 Stochiometric combustion of different fuels

The following fuels have been tested in the gasoline engine:

Gasoline is a mixture of several dozens of different compounds (mainly alkanes, alkenes, aromatic carbo-hydrants and ethers[1]). It contains approx 84%wt carbon and 16%wt hydrogen[2]; as such, as an approximation for elementary compasition, octane (C_8H_{18}) is chosen.

Liquified Petroleum gas (LPG) is a mixture of propane (C_3H_8, typically 70%vol) and butane (C_4H_{10}, typically 30%vol).

Natural gas (gronings) is a mixture consisting of mainly methane (CH_4, approx 81%vol), ethane (C_2H_6, approx 3%vol) and the inert nitrogen (N_2, approx 15%)[3]. As an approximation, it is considered to be a mixture of 85% methane and 15% nitrogen.

Biogas is a mixture of mainly methane (CH_4, typically 55-70%) and carbon dioxide (CO_2, typically 30-45%). As an aproximation, 60% CH_4 and 40% CO_2 is used.

The table below shows the calculated values of fuel and air consumption. The table shows that in comparison to gasoline, the other fuels require larger volumes of fuel/air mixture for the same amount of energy. This leads to a lower power output of the engine, called derating (see righthand column).

Table 2-1 Calculated values of fuel and air consumption

Fuel	Density (g/l)	NCV (MJ/kg)	Stoichiometric air cons (l/g)	Air cons at lambda 1.1 (l/g)	Fuel/air mix volume (l/kJ)	Derating
Gasoline	4.66*	44.43	12.77	14.05	0.32	0%
LPG	1.97	46.13	13.17	14.49	0.33	1%
Natural gas	0.75	37.81	11.00	12.10	0.36	10%
Biogas	1.11	17.65	5.14	5.65	0.37	14%

* in gaseous phase

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[1] www.nvon.nl/files/oud/nvox/nvox2008/supplementen/samenstelling_benzine.doc

[2] www.timloto.org/download/pdf_lesbrieven/brandstof/h1.pdf

[3] http://nl.wikipedia.org/wiki/Gronings_gas

NB actual derating figures for small gasoline engines that are run on biogas are higehr than the found theoretical values shown in the table. In practice, values of at least 20-25% are found.

2.1.2 Honda gasoline generator set

Tests have been carried out with a Honda EU10i gasiline generator set[4]. This set has a four-stroke engine and a generator / inverter that produces a stable 50Hz pure sinus AC output. There is annecdotal evidence that these units have a life span of more than 10,000 operational hours when properly maintanined. It is expected to have a similar performance as the larger units in the series (EU 201 and EU30i) but it is smaller and requires less fuel for full load tests.

The specifications of the EU 10i are as follows:

Table 2-2 Specifications of the Honda EU 10i generator

Model	**EU10i**
AC output	230V, 3.9 A, 50 Hz 900 VA (rated) 1000 VA (max)
DC rated output	Only for charging 12 V automotive batteries, 12V 8A
Engine model	GXH50
Engine type	4-stroke, overhead valve, single cylinder
Displacement	50 cm (3.1 cu-in)
Bore Stroke	41.8 36.0 mm (1.64 in 1.42 in)
Compression ratio	8.0:1
Engine speed	5,500 rpm (with eco throttle switch OFF)
Cooling system	Forced air
Ignition system	Full transistor
Oil capacity	0.25 l
Fuel tank capacity	2.3 l
Spark plug	CR4HSB (NGK) / U14FSR-UB (DENSO)
Operation per tank of fuel *	4.5-8h (economy)

* Source: http://www.keizerstore.nl/nl/honda-eu-10i-generator.html

The generator features an economy mode, at which the generator returns to a lwoer idle speed when there is no electrical load connected. However, when running in this mode, the generator voltage is less stable when laods vary quickly.

At the indicated consumption of 2.3 l of gasoline in 4.5 hours, at a load of 900 W, the generator efficicency would be approx 19% (fuel density of 0.75 kg/l).

The power output of the GXH50 engine at the rated speed of 5500 rpm is unknown; it is rated at 1.6 kW at 7000 rpm and 1.27 kW at 4500 rpm (2.7 Nm torque)[5]. As an estimate, a value of 1.4 kW is used[6]. Assuming an electrical efficiency of the alternator/inverter of 85%, maximum generator output values after derating would be as follows:

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[4] In the US, this set is know and the EU 1000i

[5] http://engines.honda.com/pdf/manuals/37Z4C603.pdf

[6] $\Delta P/\Delta n$ = 0.132 W/rpm; 1270+0.132*5500 = 1402W or 1.4 kW

Table 2-3 Calculated maximum engine and generator outputs

Fuel	Derating	Max engine power (kW)	Max generator output (kW)
Gasoline	0%	1.40	1.19
LPG	1%	1.38	1.18
Natural gas	10%	1.27	1.08
Biogas (theoretical derating)	14%	1.21	1.03
Biogas (practical derating)	25%	1.05	0.89

2.1.3 Testing materials

The following test meterials were used for the trials:

1. Honda EU 10i generator. A young second hand unit was purchased for testing.
2. LPG conversion kit. A pre-fabricated kit for modifying the Honda generator to run on LPG was purchased from The UK based company Hart Industries. It consists of i) a gas garretson that reduces the gas pressure to near atmospheric; ii) a venturi piece that is mounted between the carburettor and the air filter – this leads to an under pressure of approx 5 mbar; iii) a brass gas jet that is mounted inside the venturi, allowing the LPG to be sucked in (standard dimeter hole 2.1mm); and iv) hoses that connect the gas jet, garetson and LPG bottle.
3. Lamp loads. Two construction site lamps rated at 400W and 500W were used, as well as a set of incandescent lights, connected via an extension cord.
4. Power/voltage/consumption meter. For measuring power (W), voltage (V) and electricity consumption (kWh), a Voltcraft Energy check 4000 meter was used. It was plugged in between the generator and the lamp loads.
5. Fuel storage. Two different gas storages were used: i) a floating drum with a capacity of approx 60l, allowing gas to be pressurised; and ii) a plastic bag made from plastic sheet, with a capacity of approx 1.2m3 of storage under atmospheric pressure. For gasoline trials, an external fuel tank was made of a 3l canister with a fuel valve.
6. Gas meter. A standard Arctis G2.5 gas meter was used for preparing gas mixtures and measuring gas consumption.
7. Gas analyser. During some of the tests, a portable gas analyser was available (Sewerin Multitec 540) that measures CH4, CO2 and O2.
8. Scales. An Alessi digital kitchen scale (1g precision) was used for monitoring gasoline consumption.

The following fuels were used:

- Gasoline: standard EU95 gasoline was bought from a filling station
- LPG: small canisters of LPG were bought at a hardware store
- Naturel gas: gas was taken from the Dutch natural gas grid
- Biogas: a mixture of 70 parts of natural gas with 29 parts of CO2 from a small gas cylinder was used

2.2 Gasoline trials

Methods

For the gasoline trial, an external fuel tank was connected to the carburettor in order to weigh fuel before and after each trial run. A combination of lamps was connected in order to arrive at the desired electrical load. Each test run lasted for approx 40 minutes. Trial runs were carried out with the generator set in the “normal setting” and the “eco setting”.

Results

The results of the trial runs are shown in the table and the two figures below:

Table 2-4 result of the trials with gasoline (27 april 2012)

	lo-speed			**hi-speed**		
Trial	**Load (W)**	**Consumption (l/h)**	**Efficiency (%)**	**Power (W)**	**Consumption (l/h)**	**Efficiency (%)**
No load	0	0.22	0.0%	0	0.31	0.0%
¼ load	207	0.25	8.7%	208	0.36	6.2%
½ load	410	0.32	13.6%	412	0.41	10.6%
¾ load	690	0.43	17.2%	693	0.51	14.6%
Full load	885	0.57	16.6%	887	0.62	15.5%

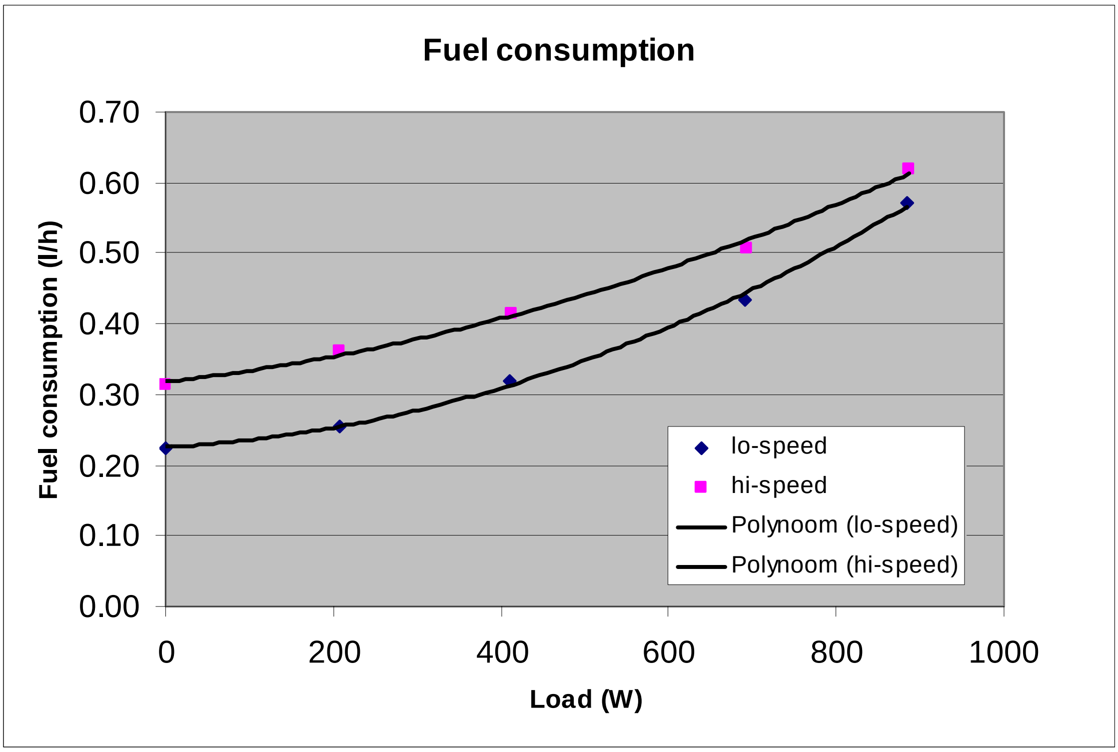

Figure 2-1 Results of fuel consumption tests with gasoline

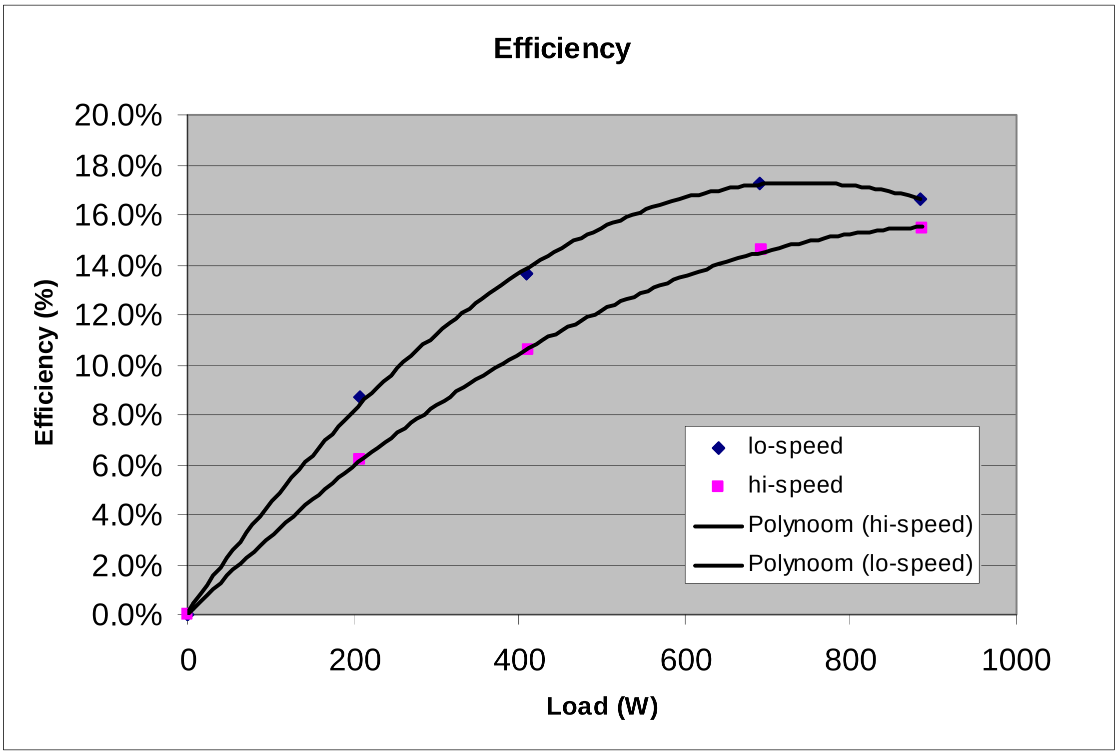

Figure 2-2 Results of efficiency tests on gasoline

The results show that the generator efficiency is well below that calculated on the basis of the rated fuel consumption (19%). There is a considerable difference between running in the normal mode and eco mode.

During a later trial run, the O2 level in the exhaust gas was measured during various loads:

-	4.40%	no load
-	2.70%	part load (ca 480W)
-	1.70%	full load (ca 880W)

Calculations on the basis of these figures point out that lambda is approx 1.1

Other observations: the generator started directly and ran smoothly throughout the trial. It ran at 1000W load for several minutes without problems.

2.3 LPG trials

Methods

For the trials with LPG, the conversion kit was mounted to the generator, using a gas jet with a 2.1 mm diameter. Initially, an LPG canister was connected to the generator through a pressure reducer, the gas meter and the garretson, but this setup resulted in a frozen pressure reducer. In following trials, the LPG was lead to the floating gas storage container, from where it was fed to the generator through the gas meter and the garetson.

Results

The results of the trials is shown in the table below:

Table 2-5 Result of the trials with LPG (6 August 2012)

Trial	Load (W)	Consumption (l/h)	Efficiency (%)
No load	0	1.68	0%
Half load	493	2.12	15.3%
Full load	880	2.84	20.5%

The trial was carried out in the eco mode only. The results show a considerably higher fuel efficiency in comparison to the gasoline trial.

2.4 Natural gas trials

Methods

The trials with natural gas were conducted using the same set-up as with the LPG. However, initial tests with the original gas jet were unsuccesful so its internal diameter was increased, step-by-step. Also, the diameter of the access in the venturi was increased.

Results

Table 2-6 below show the different configurations that were tried with natural gas as fuel.

Table 2-6 Different configurations tested with natural gas (7 August 2012)

Configuration	Gas jet diameter (mm)	Venturi diameter (mm)	Output power (W)
1	2.6	3.0	500W max
2	3.3	3.0	670W max
3	3.3	3.2	880W
4	3.3	3.3	880W (reduced efficiency)

In configurations 3 and 4 from the table above, the following results were obtained at the different loading rates:

Table 2-7 Result of the trials with natural gas in configuration 3 (7 August 2012)

Trial	Load (W)	Consumption (l/h)	Efficiency (%)	O2 in exhaust (%)
Half load	489	7	13.1%	2.50%
Full load	884	5	17.5%	2.20%

Table 2-8 Result of the trials with natural gas in configuration 4 (7 August 2012)

Trial	Load (W)	Consumption (l/h)	Efficiency (%)	O2 in exhaust (%)
No load	0	274	0.0%	4.60%
Half load	488	430	12.9%	1.40%
Full load	879	600	16.7%	0.70%

It was concluded that the best results are obtained with a diameter of 3.2mm for the venturi piece, and 3.3mm for the gas jet. In this configuration, there is no derating and the efficiency of the generator is similar to that when running on gasoline.

2.5 Biogas trials

Methods

For the trials with biogas, several test-setups were used in a seach to optimise the power output of the generator.

1. With the venturi / gas jet configuration as used with the natural gas.
2. With a second inlet / gas jet into the venturi, in order to increase the gas inlet. The venturi hole diameter is 3.0 mm, the gas jet diameter is 2.7 mm.
3. With an improvised gas mixing system, consisisting of a small PET bottle with a gas inlet and several air holes; allowing a better combustion air regulation in comparison to the setup where the original air filter is used.
4. With an atmospheric gas storage inside a bag instead of with the garretson, in order to minimise pressure losses in the gas supply system.
5. With a pre-mixed gas/air mixture directly connected to the carburettor air inlet, in order to rule out effects resulting from improper gas / air mixing.
6. With a pre-mixed gas/air mixture directly connected to the engine cylinder, in order to further reduce restrictions in the gas intake.

Biogas was simulated by mixing 70 parts of natural gas with 29 parts of CO2, arriving at 60% methane, or by mixing 75 parts of natural gas with 23 parts of CO2, arriving at 65% methane. Where air was pre-mixed, 6.8 parts of air were added to each part of biogas (for lambda 1.2) or 6.4 parts for lambda 1.1).

Results

1. Using the original venturi / gas jet configuration

When the venturi / gas jet configuration from the natural gas trials is used (gas jet hole diameter 3.3 mm, venturi entry 3.3mm), the engine does not run.

2. Using a second inlet / gas jet into the venturi

With a second gas inlet, the generator does start and run, albeit not regularly and at a low maximum output[7]. The results are shown in the table below:

Table 2-9 Result of the trials biogas (7 August 2012)

Trial	Load (W)	Consumption (l/h)	Efficiency (%)	O2 in exhaust (%)
No load	0	255	0%	7.4%
Max load	491	500	16.8%	5.6%

Before the floating gas holder was empty, the engine started running poorly, and stopped before the gas was all consumed. Measurements with the gas analyser pointed out that gas mixing inside the floating gas holder was poor: the heavier CO2 settled in the bottom of the tank, so that the initial gas coming out was of much higher methane content (more than 80%) as compared to the last parts (below 50%).

Derating was 45% as compared to the generator output, and 59% when compared to the engine output (using an estimated alternator/inverter efficiency of 85%).

3/4. Using an alternative gas mixing device

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[7] When a higher load is connected, the terminal voltage is reduced

Using a n alternative gas mixing device did not yield any better results than under (2), not with the garretson and not with the atmospheric gas storage. The engine ran erratically and it was near impossible to stabilise the generator.

5/6. Feeding pre-mixed biogas / air mixture to the engine

Using pre-mixed biogas/air mixtures led to the results[8] shown in Table 2-10 below:

Table 2-10 Result of the trials with biogas (18 September 2012)

	Test1*	**Test2**	**Test3**	**Test4**	**Test5**
Biogas methane content	60%	60%	65%	65%	60%
Lambda	1.2	1.1	1.2	1.2	1.2
Gas feed point	Carburettor	Carburettor	Carburettor	Cylinder	Cylinder
Max power	484	650	740	810	670
O2 in exhaust	5.4%	2.30%	2.70%	2.70%	2.70%
Derating generator:	46%	28%	18%	10%	26%
Derating engine	59%	45%	38%	32%	44%

* Recalculated after having reduced the length of the supply line

The generator started immediately, and ran smoothly during each of the tests. During the trials, the hose connecting the gas storage tot the generator was cut down in length (from 2.25m to 0.5m), in order to test its influence on the performance of the system. This resulted in a 38% increase in the maximum power output of the generator.

The results indicate that when using biogas with 60% methane, derating can be limited to some 45% on engine power or 26% on generator output. Derating can be reduced by:

1. Using a limited air excess (lambda of 1.1). This is a matter of finetunig of the eventual gas supply/mixing system.
2. Omitting the carburettor – although this will require a modification of the regulator and will render the generator set unfit for gasoline.

in theory, a combination of these two measures would lead to 900W generator output. However, a gas/air mixing device will eventually nee to be mounted and it will likely introduce a pressure drop similar to that over de carburettor.

An increase in the biogas methane yield also increased output power significantly. However, in practice this would require upgrading of the biogas which will require a separate washing system.

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[8] Due to the large volumes of gas / air mixture (in the order of 100 l/min) it was not possible to properly measure the gas consumption. Efficiency calculations could thus not be made.

3 BUSINESS CASE DEVELOPMENT

3.1 Case description

Starting point for the business case is a entrepreneur who wishes to start a business in energy services, for example battery charging, supply of electricity to neighbouring houses of businesses. He/she has a small capital to invest in a biogas system, generator and auxiliary equipment. Feedstock and water for the digester can be obtained at low or no costs, and the slurry can be marketed as fertiliser.

Three different cases have been calculated, based on three different ouotput capacity profiles: 1 kW, 3 kW and 5 kW.

Table 3-1 Business cases for 1, 3 and 5 kW generators running on biogas

Case	**1 kW**	**3 kW**	**5 kW**
Max continuous power output (kW)	0.9	2.7	4.5
Operating hours per day (h/d)	5	5	5
Number of batteries charged per day	5	15	25
Number of connections	1	3	5
Total energy produced per day (kWh/d)	2.7	8.2	13.7
Total biogas required per day (m3/d)	3.1	9.4	15.7
Digester size (m3)	11	33	55
Daily dung required (kg/d)	79	236	393
Daily water required (l/d)	52	157	262
Compost output (kg/d at 75% moisture)	38	114	189

In the following sections, the economics of such a system are assessed, and the sensitivity to a number of variables / uncertain parameters is tested. The most important assumptions are the following:

Table 3-2 Assumptions used in business case calculations

Assumptions		
Efficiency (biogas, part load)	15%	
Biogas energy content	21	MJ/m3
System lifetime	10000	h
Operating days per year	300	d/a
Cow dung biogas production	40	l/kg
Retention time	60	d
Dung price	0.025	USD/kg
Water price	0.010	USD/l
Price per battery charge	1.30	USD/charge
Daily fee HH connection	0.50	USD/d
Compost price	0.05	USD/kg

3.2 Investments

Table 3-3 below lists the investments in the hardware and its installation, as well as the expected (technical) lifetime. Finacial costs are calculated based on fixed annual payments with an 8% interest rate, which reflect alternative investment opportunities for the entrepreneur.

Table 3-3 Investments and financial costs

Investments (USD)	**1 kW**	**3 kW**	**5 kW**	**Lifetime (a)**
Generator	1,200	2,300	3,000	6
Biogas installation	607	1,525	1,881	10
Chargers / other equipment	300	900	1,500	10
Other (10%)	421	945	1,276	10
Total	2,529	5,670	7,657	
Annual depreciation	333	720	966	
Financial costs	458	1,000	1,343	
Total annual capital costs	**790**	**1,677**	**2,309**	

3.3 Costs and benefits

The operational costs (excluding labout costs) are shown Table 3-4 below. Oil change and spark plug changes are based on twice the recommended frequency (every 50 hrs or 10 days for oil, every 150 hrs or 30 days for spark plugs).

Table 3-4 Operational costs

Operational costs	**1 kW**	**3 kW**	**5 kW**
Dung costs (USD/d)	1.96	5.89	9.82
Daily water costs (USD/d)	0.52	0.00	0.00
Oil cost (USD/d)	0.10	0.16	0.16
Spark plug costs (USD/d)	0.17	0.17	0.17
Total operational costs (USD/d)	2.75	6.22	10.14
Total operational costs (USD/a)	826	1865	3043
Total operational costs (USD/kWh)	1.00	0.75	0.74

The table shows that the inputs for the biogas unit form the major cost items; particularly dung and to a lesser degree water.

Total operating costs are shown in Table 3-5.

Table 3-5 Operating costs

Operating costs	**1 kW**	**3 kW**	**5 kW**
Total annual capital costs	790	1,720	2,309
Total annual operating costs	826	1865	3043
Total costs	1,617	3,585	5,352
Total costs (USD per kWh)	1.96	1.45	1.30

In the smallest system, capital costs form nearly half the total operating costs. In the larger systems, this portion is somewhat smaller (around 40%), because of the economies of scale that result in lower per-unit capital costs. The table also shows that production costs are over 1.49 USD/kWh in the best case. This is high but it should be noted that these costs concern not only electricity but also the compost as a by-product.

Revenues are shown in Table 3-6. They consist mainy of battery charging fees, and to a lesser extent of compost sales and electricity sales.

Table 3-6 Revenue

Revenue	1 kW	3 kW	5 kW
Income from battery charging	6.50	19.50	32.50
income from electricity sales	0.50	1.50	2.50
Income from compost sales	2.26	6.79	11.31
Total income (USD/d)	9.26	27.79	46.31
Total income (USD/a)	2,779	8,336	13,893

The results of the cost-benefit analysis is shown in Table 3-7. It shows a payback period of 1.3 years for the smallest system, and peyback periods of less than a year for the larger ones.

Table 3-7 Results of the cost-benefit analysis

Cost/benefit analysis	1 kW	3 kW	5 kW
Total annual operating costs	826	1865	3043
Total annual revenue	2,779	8,336	13,893
Operational margin	1,952	6,471	10,850
Depreciation	333	720	966
Financial costs	458	1000	1343
Gros margin	1,162	4,751	8,541
Income per working day	7.75	31.67	56.94
Payback period	1.3	0.9	0.7

The entrepreneur thus earns an annual return on his invested capital, but also a margin that should cover the time that he/she puts into the operation of the unit. If the time requirements are a half working day per day, the income per working day would be 7.75, 31.96, and 56.94 USD per working day respectively.

3.4 Sensitivity analysis

An assessment of the sensitivity of the financial results to variations in some of the less certain parameters / variables has been carried out. Specifically, the following parameters have been tested:

Parameter	Range
- Generator derating	(0 - 25% - 50%)
- Generator efficiency	(15% - 13% - 11%)
- Dung price	(0 - 25 - 50 USD/t)
- Water price	(0 - 10 - 20 USD/m3)
- Battery charge price	(1.5 - 1.3 - 1.1 USD/ch)
- Compost price	(100 – 50 – 0 USD/t)

The results for the smallest (1 kW) setup are shown in the figures below. For the larger systems, the trends are the same. They results show the following trends:

- Generator efficincy reductions over the tested range have a small influence on payback period.
- Generator derating is a more important parameter, although its effect remains limited. With 25% and 50% derating, per-kWh production costs increase to 2.10 and 2.35 USD/kWh (or 7% and 20%) respectively.
- Dung is the most important cost item. If dung can be obtained for free, the payback period drops to 1 year. In comparison, variations in the water price has a very limited effect.

- Compost sales are an important source of income; without it, payback period rises to nearly 2 years. Changing battery charging fees has a limted effect.

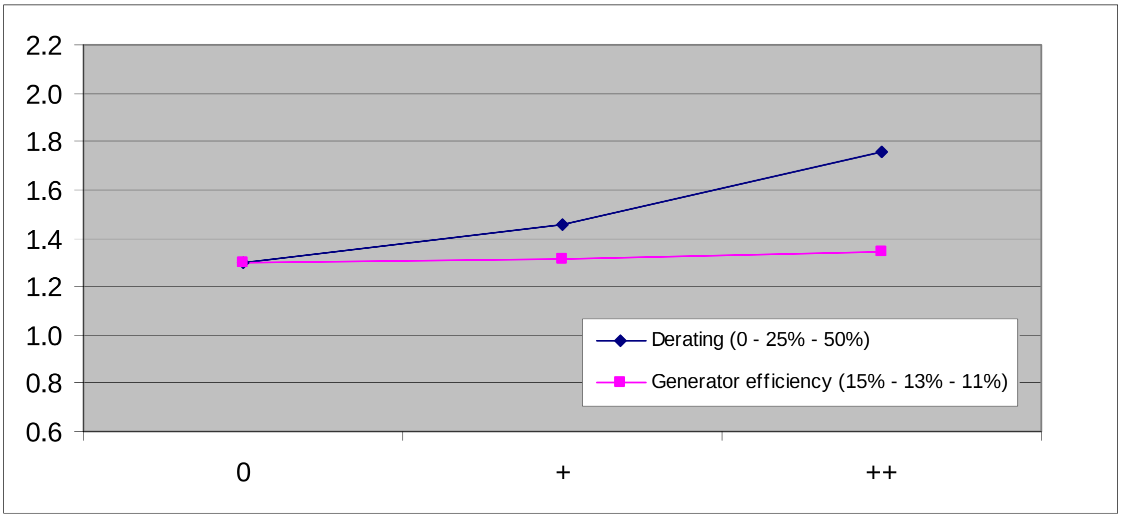

Figure 3-1 Sensitivity to derating and generator efficiency

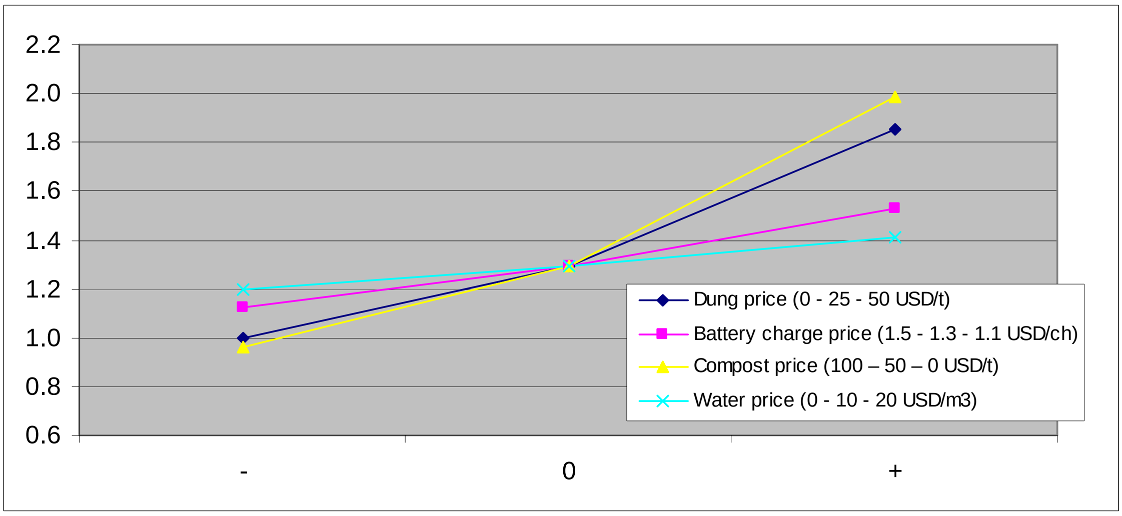

Figure 3-2 Sensitivity to dung price, battery charging price, compost price and water price

3.5 Comparison with other energy sources

In order to place the results in a wider context, per-kWh production cost estimates were made for cases with diesel and PV. Figure 3-3 below shows the results.

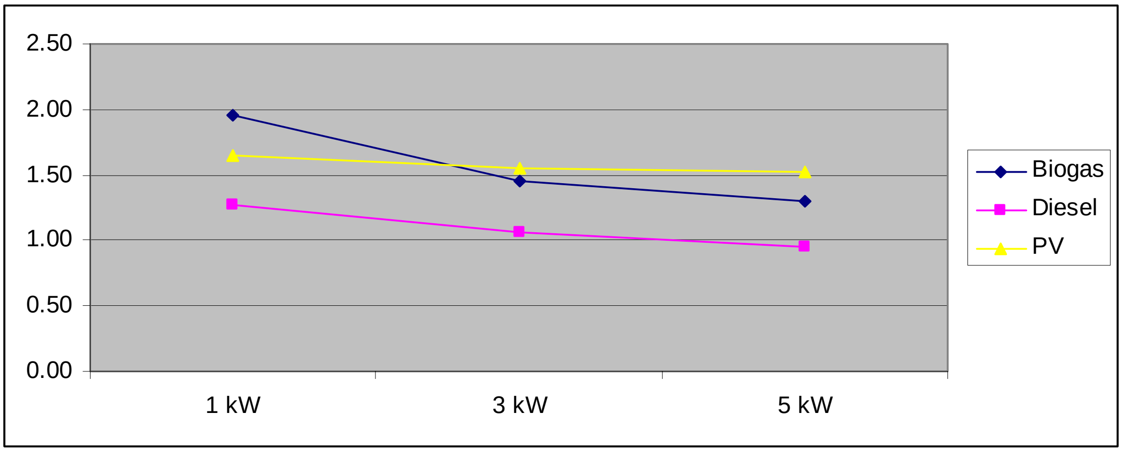

Figure 3-3 Comparison to other energy sources

What becomes clear is that PV is competitive only in the smallest segment; in this scale range, economies of scale are limited with PV, in contrast to the other two options. Also, costs with PV are almost entirely made up of investment costs, which may form a barrier to a local entrepreneur who usually has a limited investment capacity.

Secondly, production with diesel is a more attractive option over the full scale range. In addition, investment costs are considerable lower. Under the standard circumstances therefore, diesel is the more attractive option.

Only if dung costs are set to zero, biogas becomes more attractive than diesel. In such a case, production costs are equal to that of diesel in the case of 1 kW. In the larger cases, production costs are much lower (0.73 and 0.58 USD/kWh in the 3 kW and 5 kW cases, respectively).

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

4.2 Recommendations

Additional testing

- ignition timing