REFEREED PAPER

THE INCREASING ROLE OF ANAEROBIC DIGESTION AS A SOURCE OF ENERGY

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Abstract

The increasing importance of high rate anaerobic digestion in the sugar industry is reviewed. Reactor technology and associated microbiology is outlined, and production of biogas from various feedstocks is considered, together with potential uses for the biogas. Opportunities for replacing diesel fuel with biomethane are highlighted and illustrated by results of an energy balance around a hypothetical cane energy estate producing only ethanol and power.

Keywords: anaerobic digestion, biogas, biorefinery, energy balance, ethanol, distillery

Introduction

The increasing value of energy, especially non-fossil energy, encourages efforts towards energy efficiency and maximum use of alternative sources of energy. This in turn encourages careful consideration of opportunities for deriving energy from all components of the sugarcane plant and from all stages of processing, particularly relevant to biorefineries.

Various energy conversion techniques are applicable to components of the sugarcane plant, including fermentation of the sugar component, direct burning of the fibre component, indirect incineration of the fibre through gasification followed by combined cycle electricity generation or Fischer-Tropsch reaction of gas components to produce liquid fuel. Biological gasification via anaerobic digestion is attracting increasing attention because it enables energy (methane) recovery from high moisture feedstocks (e.g. molasses) without needing energy-intensive distillation or pre-drying.

This paper reviews various options for anaerobic digestion and highlights the increasing potential to use the digestion process to produce a replacement for diesel fuel.

Biology and Technology

Terminology and abbreviations

Biogas	The raw gas arising from anaerobic digestion. Biogas contains about 60% methane and 40% carbon dioxide.
Biomethane	Purified biogas containing 96-99% methane.
CNG	Compressed natural gas.
COD	Chemical oxygen demand (an indicator of the amount of digestible material).
EGSB	Expanded granular sludge blanket.
LNG	Liquefied natural gas.

LHV/HHV Lower/higher heating value.
NGV Natural gas vehicle.
R South African Rand (US$1.00 ~ R7.50).
UASB Upflow anaerobic sludge blanket (a type of anaerobic digester).
VOC Volatile organic compounds.

The anaerobic digestion process

Anaerobic digestion is the breakdown of organic compounds by microorganisms in a low or no oxygen environment. The process is synergistic in that four biochemical steps (Figure 1) are carried out simultaneously by different types of microorganisms. The major end-product is biogas, which contains mainly methane and carbon dioxide.

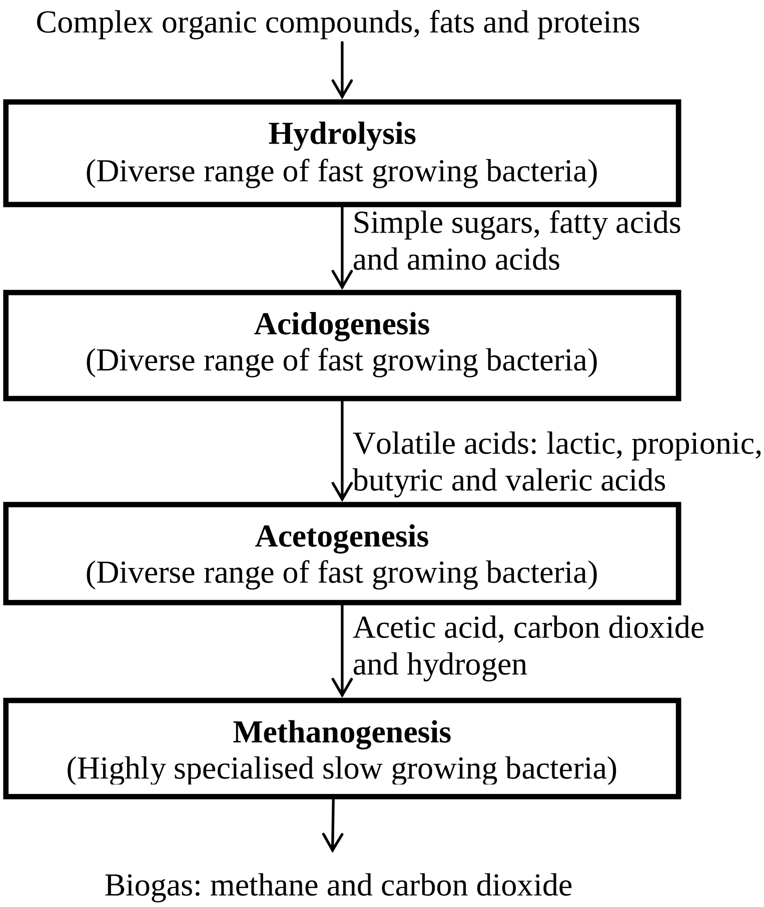

Figure 1. The anaerobic digestion process.

In the final stage of the process, highly specialised, delicate and slow-growing bacteria produce methane and carbon dioxide via the following pathways (Rapport *et al.*, 2008):

Acetotrophic methanogenesis: $CH_3COOH \longrightarrow CO_2 + CH_4$
Hydrogenotrophic methanogenesis: $CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$
Methylotrophic methanogenesis: $4CH_3OH + 6H_2 \longrightarrow 3CH_4 + 2H_2O$

Designs of anaerobic digesters

The main purpose of an anaerobic digester is to ensure contact between active biomass and organic matter such that the organic matter is digested and stabilised by the biomass. There are many different designs, which include but are not limited to:

- Anaerobic hybrid reactor (AHR)
- Anaerobic sequencing batch reactor (ASBR)
- Continuously stirred tank reactors (CSTR)
- Expanded granular sludge bed (EGSB)
- Fixed film reactors (FFR)
- Fluidised bed reactors (FBR)
- Upflow anaerobic sludge blanket (UASB).

Most of the designs are variations of the CSTR, FFR or UASB, or are a combination of two different designs. The market trend is towards high rate reactors requiring some form of internal circulation, additional to the agitation caused by rising gas (Kassam *et al*., 2003). Such reactors can digest up to 30 kg COD/m^3/day, but may not be suitable for feed rich in solids. The increasing interest in digesting energy crops (high solids) presents a new challenge for reactor design.

It must be appreciated that anaerobic digestion in high rate reactors is a delicate process requiring experienced operators. There are, however, options for 24-hour remote control of digesters by experienced operators providing this service from ‘call centres’.

Each reactor type has particular operational advantages applicable to different feed material, influenced mainly by the solids content. The major operational challenge is to maintain a high concentration of methanogenic bacteria in the reactor so as to ensure that acids formed in the early stages by other bacteria do not accumulate. This challenge is difficult because the methanogens grow relatively slowly, but systems for ensuring retention of live biomass in the reactor enable the necessary accumulation of methanogens.

In simple open anaerobic dams the upper layers are not protected from oxygen and are therefore not suitable for methanogens, most of which are killed by oxygen. The importance of using a properly designed reactor is illustrated by the fact that the maximum loading for open shallow systems is about 0.08 kg COD/m^3/d, whereas most closed reactors can digest more than 10 kg COD/m^3/d. However, the use of closed systems is generally not economical where the feed COD concentration is less than 2000 mg/L.

Feedstock for anaerobic digesters

Historically, the major use for anaerobic digesters has been for digesting sewage sludge and slurries of animal manure. Disposal of industrial wastes then followed with applications in the wine (Ross, 1980), potato, brewing and sugar industries. Early application of high rate digestion in the beet sugar industry is described by Lettinga *et al*. (1980), and application to vinasse began in Brazil at about the same time.

More recently, interest has focused on the digestion of energy crops and agricultural residues, including glycerol from biodiesel production. International research consortia make results readily available on web sites such as www.biogasmax.eu. An indication of potential biogas production from different substrates is given in Table 1.

Table 1. Indicative values of biogas yields from various feedstocks.

Feedstock	Total solids %	Volatile solids %TS	Biogas yield m^3/tonne (VS)
Cattle/pig slurry	10	70-85	15-25
Grass silage	28	90	160-200
Corn silage	33	90	200-220
Sorghum	25	90	295-372
Grass	25	90	298-467
Poultry	20	70-80	30-100
Vinasse*	5	80-95	350-450

*Baez-Smith (2006)
http://www.adnett.org/dl_feedstocks.pdf
http://www.biogas-info.co.uk/index.php/biogas-yields.html

Gas characteristics and uses of biogas and biomethane

Characteristics

Typical composition of biogas is:

Methane	50 - 60%
Carbon dioxide	40 - 50%
Nitrogen	1 - 5%
Hydrogen sulphide	ca. 1500 mL/m^3

In addition there is water vapour, traces of various volatile organic compounds (VOC) and possibly siloxanes. The siloxanes generally appear only when sewage has been digested. They are derived from cosmetics and shampoos, and may cause problems of excess component wear when biogas is used in internal combustion engines or turbines. Hydrogen sulphide and water need to be removed if the biogas is to be used in applications where these components cause corrosion or blockages (due to formation of methane hydrates).

Some properties of the components of biogas (not biogas itself) are shown in Table 2. Purification of the biogas may be necessary, depending on intended use. Purified biogas is referred to as 'biomethane' (96-99% methane) and has the properties of methane. The carbon dioxide in biogas causes this gas to have much lower energy content than biomethane, often causing confusion in energy calculations when this difference between biogas and biomethane is not appreciated.

Table 2. Properties of individual components of biogas.

Property	CH_4	CO_2	N_2	H_2S
Relative density vs air (at stp)	0.554	1.52	0.967	1.189
Critical temperature (°C)	-82.7	31	-146.9	100
Limit of flammability in air (%)	5-15			4.3-46
Solubility in water (mL/L at 20°C)	35			
Density (g/L at 20°C)	0.668			
HHV (kJ/kg)	55 387			
LHV (kJ/kg)	49 855			

Various 'off-the-shelf' technologies are available for gas cleaning, and numerous companies specialise in the selection and provision of appropriate systems. The systems include wet scrubbing systems, various dry absorption systems (Sitthikhankaew *et al*., 2011), organic membranes and even biological oxidation of H_2S (Gadde, 2006). The dry absorption systems are less expensive than wet systems and are generally used where it is not necessary to remove CO_2 (www.appliedfilter.com).

The lower heat value (LHV) is the energy available after water and combustion products have been vaporised. Comparison of the LHV of methane with that of other fuels is given in Table 3.

Table 3. Energy densities of various forms of fuels.

Fuel	Form	Units	Energy content*
Biogas (50% CO_2)	Gas	MJ/kg	~25
Methane	Gas at 1 bar/15°C	MJ/kg MJ/L	55.6 0.0378
Natural gas (96-99% methane) (similar to biomethane)	Gas at 1 bar/15°C	MJ/kg MJ/L	53.6 0.0364
Compressed natural gas (CNG) (similar to compressed biomethane)	Gas at 250 bar	MJ/kg MJ/L	53.6 9
Liquefied natural gas (LNG) (similar to liquefied biomethane)	Liquid at -160°C	MJ/kg MJ/L	53.6 22.2
Diesel	Liquid	MJ/kg MJ/L	45.4 38.6
Petrol	Liquid	MJ/kg MJ/L	47.2 34.0
Ethanol	Liquid	MJ/kg MJ/L	26.7 21.1
Bagasse	50% moisture	MJ/kg	~7

*These are indicative figures derived from a variety of literature sources, each of which gives slightly different figures.

Options for use of biogas

Figure 2 gives an overview of options for use of biogas, with most options requiring prior purification to produce biomethane. Three major options are direct combustion, fuelling engines and sales to natural gas providers.

Direct combustion is the simplest option and mainly involves either process steam cogeneration or electricity cogeneration in gas turbines. Engine fuelling involves either stationary engines for electricity generation or mobile engines on motor vehicles, ships or trains.

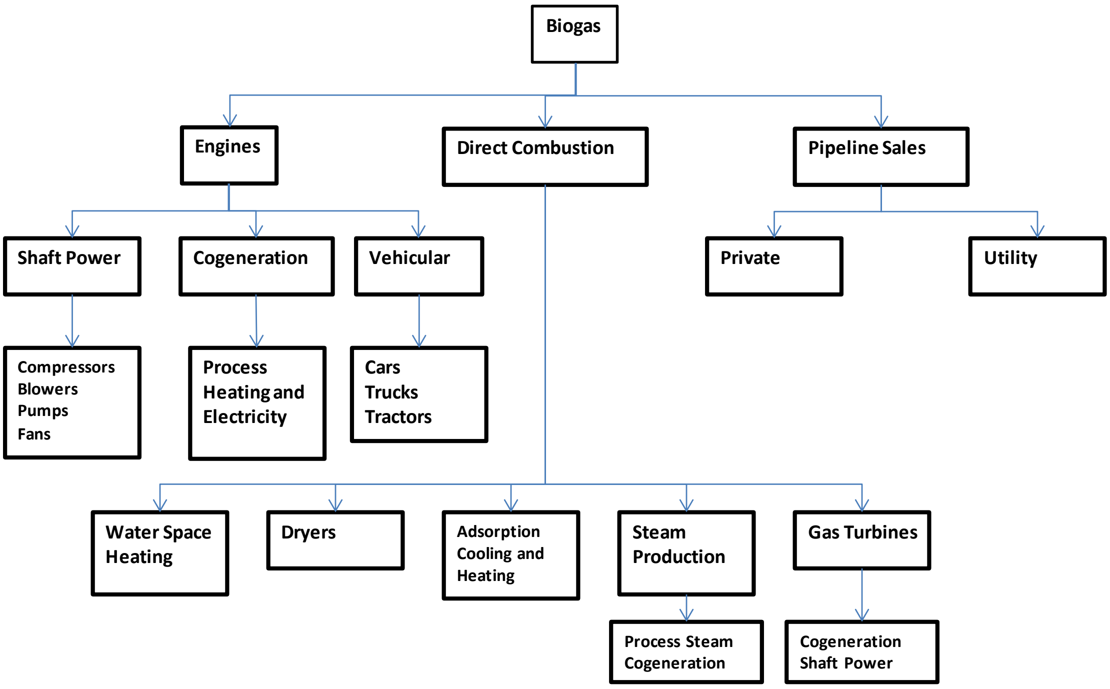

Figure 2. Options for the use of biogas.

Sugar industry perspective and case studies

Leal (2007) gives an excellent review of current and future energy challenges and opportunities in the sugarcane industry, including a scenario in which biogas is involved. He concludes that there is scope for cane-based energy factories (no sugar production) to increase energy conversion efficiency (cane energy to marketable energy) from the current 29% to about 51% by 2020. This involves producing biogas and using futuristic technologies to improve energy recovery from lignocellulose.

At present-day sugarcane factories the feedstocks with possible economic potential for biogas production are molasses and vinasse if an attached ethanol distillery is present. When ethanol is being made, the molasses is best used for ethanol production. When ethanol is not being made, the molasses generally finds value for uses other than biogas production. However, where transport costs are high there may be economic advantage in using the molasses for on-site biogas production.

Where vinasse is produced its value is as a source of nutrients for return to cane fields. This value is not diminished if the vinasse is subjected to anaerobic digestion prior to distribution to fields. The decision on whether to invest in anaerobic digestion depends on the opportunities for profitable use of the biogas. In India, where there are incentives to sell electricity to the grid, a number of sugar factories with distilleries produce biogas and burn it in the factory boilers as an additional source of fuel (personal visit).

Electricity generation
In southern Africa, the price offered for electricity does not justify investment in biogas production and associated power generation equipment for electricity sales. Consideration of

a hypothetical cane energy estate growing 20 000 ha of cane under tropical conditions with irrigation led to a preliminary assessment (Table 4).

Table 4. Preliminary assessment of electricity production using biogas and gas engines.

Assumptions: 300 m^3/h of vinasse at COD concentration of 30 000 mg/L (216 t COD/d)		
Item	**Quantity**	**Units**
Capital cost of digesters and gas engines	**140**	million Rand
Methane generation	58 320	Nm^3/d
Power equivalent (in gas)	24.2	MW
Electrical power equivalent (40% conversion efficiency)	9.7	MW
Revenue at R0.20/kWh	11.73	million Rand
Carbon credits for fuel switching (at 8 Euros/t)	2.4	million Rand
Operating costs including engine overhauls	5	million Rand
Net annual revenue	**9.1**	million Rand

Clearly this is not a viable option. No credit has been given for the thermal energy (9.7 MW) available from the system. If it saved coal at R500/t it would be worth R4 million per annum but this would still involve an unacceptable pay-back period of about 10 years. Leal (2007) states categorically that under Brazilian conditions the capital cost of anaerobic digesters is too high to justify biogas-based electricity sales.

Where a factory buys electricity, it is reasonable to argue that the value of the electricity generated on-site is equivalent to the value of the price that would have been paid to buy the electricity. Even this scenario is generally not attractive for biogas-based electricity.

This assessment was based on gas engines because these reciprocating, internal combustion engines are increasingly being fuelled with gas from digesters and are highly efficient in energy conversion (38-40% conversion to electricity, compared to 25% with most existing boiler pressures). Heat is captured from the exhaust and engine cooling system, giving a total energy capture exceeding 80% (combined heat and power). It is not necessary to remove CO_2 from the biogas fuel. Jenbacher engines have the major market share with 290 installations. Engine sizes vary between 0.25 and 3.0 MW generation capacity (www.gejenbacher.com).

Vehicle fuel

In the absence of incentives to sell electricity made from biogas, it is worth considering whether the sugar industry could use it as a vehicle fuel. Diesel fuel is a major energy cost for production and delivery of cane. On-site production of a diesel replacement via biogas seems to be an approaching opportunity for cane energy estates.

The special case for biogas use as vehicle fuel on cane estates

Advances in use of natural gas as vehicle fuel

In response to the foreseen shortages of crude oil, attention has turned to natural gas as an alternative source of energy. In recent years, considerable progress has been made in locating new gas fields and in developing technologies for recovering and using the gas. Developments in vehicle engines capable of using the gas as fuel have been phenomenal over the past five years, such that most major motor manufactures now offer gas engines. In addition, suppliers of reliable equipment for retrofitting diesel and petrol engines for methane fuel have entered the market. Simultaneously, progress has been made in technologies for compressing the gas and using it in mobile applications, with opportunities for rapid refuelling. Refuelling stations are increasing in number and there are so-called ‘blue routes’ along which access to methane fuel is assured.

The development of technologies related to natural gas opens opportunities for biogas because, being predominantly methane, both gases are essentially the same. The biogas industry can therefore ‘ride’ on the expertise and marketing of the huge natural gas industry, including expertise in gas cleaning and natural gas vehicles (NGVs). International co-operation in research and open sharing of results (e.g. Svensen and Rydehell, 2010) is exceptional and of considerable potential benefit to biorefineries associated with the sugar industry.

For use as a vehicle fuel, biogas must be upgraded to the following CNG standard (SAE J1616):

CH_4	94-98%
CO_2	0.5-2.0%
H_2S	Not detectable
H_2O	<-40°C Dew point

The trend towards increased use of NGVs is illustrated in Figure 3, which highlights rapid increases since 2006. Lists of NGV models available in various countries are given by Anon (2009) and confirm that all major motor manufacturers offer NGVs, including large engines for buses, trucks and agricultural tractors. Reports on vehicle performance are generally positive, with the major benefit being reduced fuel costs. The need for mechanic retraining is emphasised (Anon, 2009).

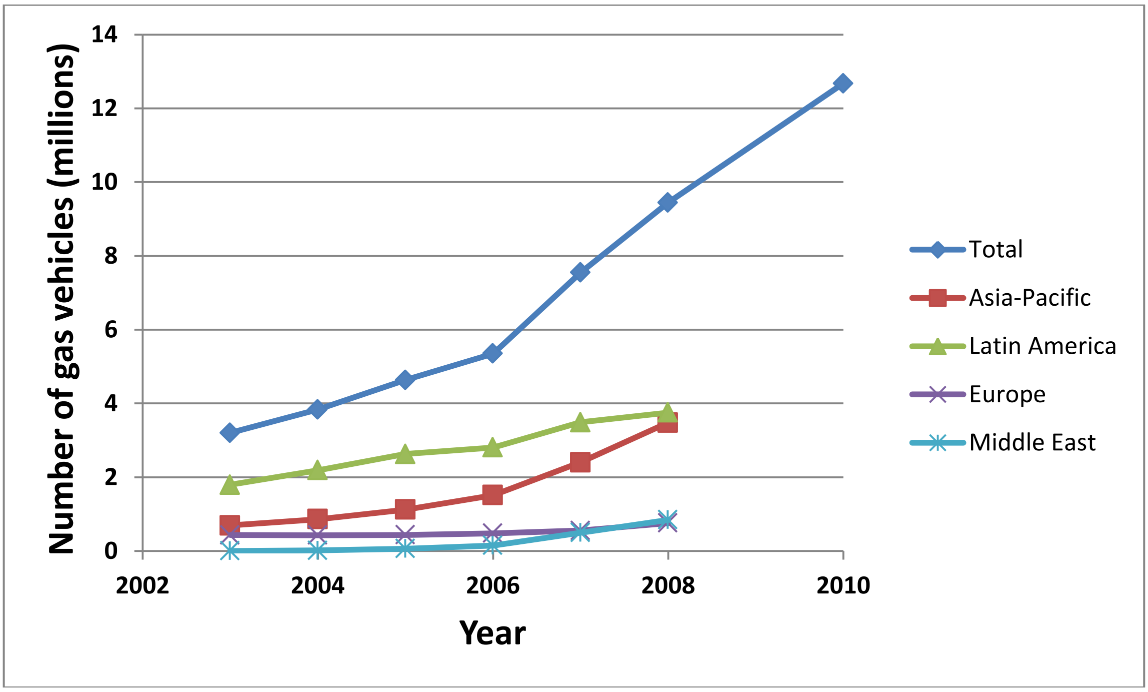

Figure 3. Recent increases in natural gas vehicles (Anon, 2009 and www.iangv.org).

The anticipated continued growth of NGVs is shown in Figure 4.

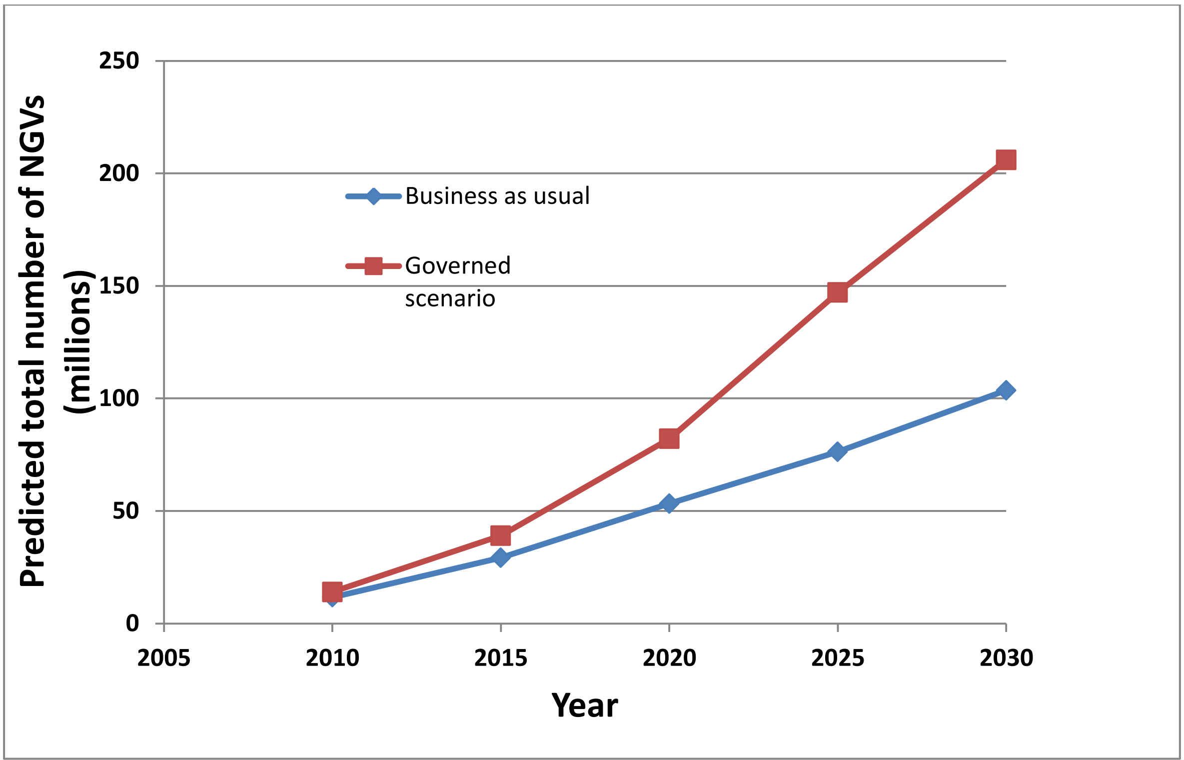

Figure 4. Anticipated increases in NGVs (Anon, 2009).

Figure 3 and 4 suggest that NGV technology is now well established and becoming increasingly attractive. This includes all aspects of engine technology, gas cleaning, compression, storage and refuelling. The technology could be particularly suited to sugarcane ‘energy estates’ in southern Africa because:

- It provides a replacement for diesel, which is a high cost item in sugar production and generally has to be transported over long distances to rural areas.
- For energy estates producing ethanol, vinasse would be available as a feedstock for biogas production, yet the vinasse would retain its nutrient value for recycling on the estate after anaerobic digestion. Sulphur removed during cleaning of biogas can be recovered for nutrient recycling.
- The centralised co-ordination of biomethane production and vehicle operations on an estate facilitates refuelling and eliminates the need for external gas refuelling stations. Agricultural tractors can be refuelled in-field by a ‘mother vehicle’; transport vehicles would regularly be in the vicinity of the refuelling station at the factory.
- The availability of dual fuel engines with immediate switching between fuels means that vehicle operations can continue when the supply of compressed methane is interrupted.
- Vehicle engines, both diesel and spark ignition, can be retrofitted for use with methane (without losing their ability to run on liquid fuel).
- There are environmental benefits in terms of CO_2 emissions for the fuel production process and in terms of noxious components of exhaust emissions.

As proof of concept in the sugar industry, it is notable that in 1989 the Sao Joao distillery in Brazil was running 41 vehicles on biomethane (personal visit 1989). A variety of engines, including Mercedes Benz, General Motors and Massey Ferguson, were being tested.

Considerable technical progress has been made since that time, with widespread introduction of electronic engine management systems being helpful for dual fuel engines.

A hypothetical case study

Again, consideration of a hypothetical cane energy estate growing 20 000 ha of cane under tropical conditions with irrigation, led to a preliminary assessment (Table 5). This assessment shows that if dual fuel diesel engines are used with the normal 70:30 gas: diesel blend, the amount of gas required would have a diesel equivalent of 8.4 million L. The potential gas production has a diesel equivalence of 9 million L, so there is a good balance of production and consumption.

The capital and running cost of the system (including gas cleaning) has not been ascertained accurately, but is likely to be similar to that for the electricity generation assessment, assuming that the additional gas cleaning equipment required for motor fuel has similar costs to the stationary engines for the electricity generation assessment. It is evident that if the capital cost is R140 million, then the payback time is attractive if R72 million is saved annually by diesel replacement. An additional cost, however, would be the dual fuel engines. Retrofitting, including gas cylinders, costs about R55 000 for a small vehicle, and new dual fuel vehicles are generally about 15% more expensive than standard liquid fuel versions (Anon, 2009).

Table 5. Assessment of diesel replacement with biomethane from vinasse.

Feedstock assumptions		
1. 20 000 ha irrigated cane producing ethanol only (no sugar) 2. 330 t/h vinasse with COD of 25 000 mg/L 3. 36-week season		
Diesel equivalence of biomethane		
Item	**Quantity**	**Units**
Biogas production	0.5	Nm^3/kg COD consumed
COD abatement	65	%
Methane % biogas	60	%
Methane solubility	35	mL/L water at 20°C
Recoverable methane	0.31	Nm^3/kg COD consumed
Energy in methane	55	MJ/kg
Diesel equivalence of methane	**9**	million L/an
Annual value of diesel replacement	**72**	R million (corrected for agric. tax rebates)
Annual diesel and gas requirement		
Annual diesel required/t cane	5	L/t cane (production, harvest and delivery)
Total annual requirement	12	million L
Diesel:gas ratio	30:70	energy basis (for compression ignition engine)
Potential for gas consumption	**8.4**	million L diesel equivalent (70% of 12)
Remaining diesel requirement	3.6	million L

A separate indication of production costs of biomethane for vehicle fuel (unpublished data[1]) is:

Gas production via anaerobic digestion	16-26 UK pence/kg
Upgrading to vehicle fuel quality	10-20
Compression and storage	10

The preliminary economic assessment and recent technical developments suggest that vehicle fuel manufacture from vinasse deserves careful consideration in future sugarcane projects.

Summary and Conclusions

High capital costs of biomethane production, together with relatively low value of electricity in the Southern Africa region, preclude the development of a viable business based on electricity sales from biomethane.

The production and use of biomethane as a replacement for diesel fuel on sugarcane estates warrants close consideration, especially because the economics look attractive and there is a world trend towards natural gas as a vehicle fuel. Biomethane, being similar to natural gas, will benefit from technical developments and marketing initiated by the natural gas industry.

In the longer term, the use of anaerobic digestion for extracting maximum energy from energy crops and crop residues seems worthy of investigation. Early results from Europe suggest that this approach may give access to cellulose as well as sugars in the crops.

Acknowledgment

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