



Biogas Digest

Volume I

Biogas Basics



**Information and Advisory Service
on Appropriate Technology**



Imprint

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Biogas Basics

What is biogas?

Biogas originates from bacteria in the process of bio-degradation of organic material under anaerobic (without air) conditions. The natural generation of biogas is an important part of the biogeochemical carbon cycle. Methanogens (methane producing bacteria) are the last link in a chain of micro-organisms which degrade organic material and return the decomposition products to the environment. In this process biogas is generated, a source of renewable energy.

Biogas and the global carbon cycle

Each year some 590-880 million tons of methane are released worldwide into the atmosphere through microbial activity. About 90% of the emitted methane derives from biogenic sources, i.e. from the decomposition of biomass. The remainder is of fossil origin (e.g. petrochemical processes). In the northern hemisphere, the present tropospheric methane concentration amounts to about 1.65 ppm.

Biology of methanogenesis

Knowledge of the fundamental processes involved in methane fermentation is necessary for planning, building and operating biogas plants. Anaerobic fermentation involves the activities of three different bacterial communities. The process of biogas-production depends on various parameters. For example, changes in ambient temperature can have a negative effect on bacterial activity.

Substrate and material balance of biogas production

In principle, all organic materials can ferment or be digested. However, only homogenous and liquid substrates can be considered for simple biogas plants: faeces and urine from cattle, pigs and possibly from poultry and the wastewater from toilets. When the plant is filled, the excrement has to be diluted with about the same quantity of liquid, if possible, the urine should be used. Waste and wastewater from food-processing industries are only suitable for simple plants if they are homogenous and in liquid form. The maximum of gas-production from a given amount of raw material depends on the type of substrate.

Composition and properties of biogas

Biogas is a mixture of gases that is composed chiefly of:

- **methane** (CH_4): 40-70 vol.%
- **carbon dioxide** (CO_2): 30-60 vol.%
- **other gases**: 1-5 vol.%
including
 - hydrogen (H_2): 0-1 vol.%
 - hydrogen sulfide (H_2S): 0-3 vol.%

Like those of any pure gas, the **characteristic properties** of biogas are pressure and temperature-dependent. They are also affected by the moisture content. The factors of main interest are:

- change in volume as a function of temperature and pressure,
- change in calorific value as a function of temperature, pressure and water-vapor content, and
- change in water-vapor content as a function of temperature and pressure.



The **calorific value** of biogas is about 6 kWh/m³ - this corresponds to about half a litre of diesel oil. The net calorific value depends on the efficiency of the burners or appliances. Methane is the valuable component under the aspect of using biogas as a fuel.

Utilization

The history of biogas utilization shows independent developments in various developing and industrialized countries. The European biogas-history and that of Germany in particular, as well as developments in Asian countries form the background of German efforts and programmes to promote biogas technology worldwide.

Normally, the biogas produced by a digester can be used as it is, just in the same way as any other combustible gas. But it is possible that a further treatment or conditioning is necessary, for example, to reduce the hydrogen-sulfide content in the gas. When biogas is mixed with air at a ratio of 1:20, a highly explosive gas forms. Leaking gas pipes in enclosed spaces constitute, therefore, a hazard. However, there have been no reports of dangerous explosions caused by biogas so far.

A first overview of the physical appearance of different types of biogas plants describes the three main types of simple biogas plants, namely balloon plants, fixed-dome plants and floating-drum plants.

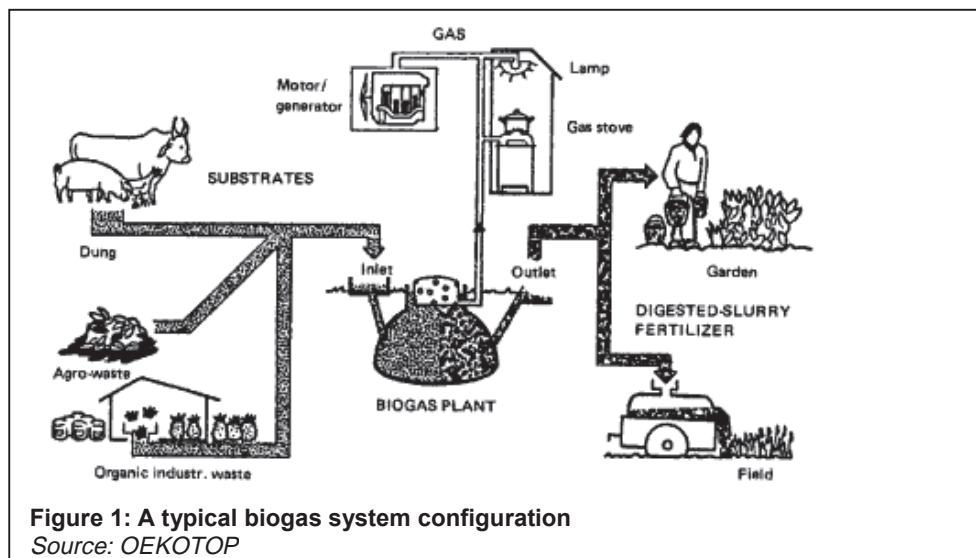


Figure 1: A typical biogas system configuration
Source: OEKOTOP

The Benefits of Biogas Technology

Well-functioning biogas systems can yield a whole range of benefits for their users, the society and the environment in general:

- production of energy (heat, light, electricity) ;
- transformation of organic waste into high quality fertilizer;
- improvement of hygienic conditions through reduction of pathogens, worm eggs and flies;
- reduction of workload, mainly for women, in firewood collection and cooking.
- environmental advantages through protection of soil, water, air and woody vegetation;
- micro-economical benefits through energy and fertilizer substitution, additional income sources and increasing yields of animal husbandry and agriculture;
- macro-economical benefits through decentralized energy generation, import substitution and environmental protection

Thus, biogas technology can substantially contribute to conservation and development, if the concrete conditions are favorable. However, the required high investment capital and other limitations of biogas technology should be thoroughly considered.

The Costs of Biogas Technology

An obvious obstacle to the large-scale introduction of biogas technology is the fact that the poorer strata of rural populations often cannot afford the investment cost for a biogas plant. This is despite the fact that biogas systems have proven economically viable investments in many cases.

Efforts have to be made to reduce construction cost but also to develop credit and other financing systems. A larger numbers of biogas operators ensures that, apart from the private user, the society as a whole can benefit from biogas. Financial support from the government can be seen as an investment to reduce future costs, incurred through the importation of petrol products and inorganic fertilizers, through increasing costs for health and hygiene and through natural resource degradation.

Fuel and Fertilizer

In developing countries, there is a direct link between the problem of fertilization and progressive deforestation due to high demand for firewood. In many rural areas, most of the inhabitants are dependant on dung and organic residue as fuel for cooking and heating. Such is the case, for example, in the treeless regions of India (Ganges plains, central highlands), Nepal and other countries of Asia, as well as in the Andes Mountains of South America and wide expanses of the African Continent. According to data published by the FAO, some 78 million tons of cow dung and 39 million tons of phytogenic waste were burned in India alone in 1970. That amounts to approximately 35% of India's total noncommercial/nonconventional energy consumption.

The burning of dung and plant residue is a considerable waste of plant nutrients. Farmers in developing countries are in dire need of fertilizer for maintaining cropland productivity. Nonetheless, many small farmers continue to burn potentially valuable fertilizers, even though they cannot afford to buy chemical fertilizers. At the same time, the amount of technically available nitrogen, potassium and phosphorous in the form of organic materials is around eight times as high as the quantity of chemical fertilizers actually consumed in developing countries. Especially for small farmers, biogas technology is a suitable tool for making maximum use of scarce resources: After extraction of the energy content of dung and other organic waste material, the resulting sludge is still a good fertilizer, supporting general soil quality as well as higher crop yields.

Public and Political Awareness

Popularization of biogas technology has to go hand in hand with the actual construction of plants in the field. Without the public awareness of biogas technology, its benefits and pitfalls, there will be no sufficient basis to disseminate biogas technology at grassroots level. At the same time, awareness within the government is essential. Since impacts and aspects of biogas technology concern so many different governmental institutions (e.g. agriculture, environment, energy, economics), it is necessary to identify and include all responsible government departments in the dissemination and awareness-raising process.

History of Biogas Technology

Europe/Germany

- 1770 The Italian Volta collected marsh gas and investigated its burning behavior.
- 1821 Avogadro identified methane (CH₄).
- 1875 Propoff states that biogas is produced under anaerobic conditions.
- 1884 Pasteur researched on biogas from animal residues. He proposed the utilization of horse litter to produce biogas for street-lighting.
- 1906 First anaerobic wastewater-treatment plant in Germany.
- 1913 First anaerobic digester with heating facility.
- 1920 First German sewage plant to feed the collected biogas into the public gas supply system.
- 1940 Addition of organic residues (fat) to increase sewage gas production.
- 1947 Research demonstrates that the dung of one cow can give a hundred times more gas than the feces of one urban inhabitant.
Establishment of the first working group on biogas in Germany.
- 1950 Installation of the first larger agricultural biogas plant.
- 1950s Nearly 50 biogas plants are built, fed by litter mixed with water and dung. Low oil prices and technical problems lead to the shutdown of all but two plants.
- 1974 After the first 'energy crisis', increased promotion of research on and implementation of agricultural biogas technology by the EC and federal departments.
- 1985 75 biogas plants are listed (built or planned). Biogas slurry is increasingly used as liquid manure.
- 1990 Progress due to guaranteed prices for biogas-generated electricity. Progress in optimizing the mixture of substrates, the use of biogas for different purposes and technology details.
- 1992 Foundation of the German biogas association 'Fachverband Biogas'
- 1997 More than 400 agricultural biogas plants exist in Germany.

China and India

The history of biogas exploration and utilization in China covers a period of more than 50 years. First biogas plants were built in the 1940s by prosperous families. Since the 1970s biogas research and technology were developed at a high speed and biogas technology was promoted vigorously by the Chinese government. **In rural areas, more than 5 million small biogas digesters have been constructed and, currently, over 20 million persons use biogas currently as a fuel.**

In India, the development of simple biogas plants for rural households started in the 1950s. A massive increase in the number of biogas plants took place in the 1970s through strong government backing. Meanwhile, more than one million biogas plants exist in India.

The historical experiences in Germany, China and India demonstrate clearly, how biogas development responds to favorable frame conditions. In Germany, biogas dissemination gained momentum through the need for alternative energy sources in a war-torn economy and during an energy crisis or later by the change of electricity pricing. In India and China it was a strong government program that furthered the mass dissemination of biogas technology.

German promotion of biogas technology in the south

In the late 1970's, triggered by Schuhmacher's 'Small is Beautiful', appropriate, simple technologies entered the arena of development work in the South. Not Northern high-tech, but innovative, affordable, simple and traditional technologies, it was believed, were the

remedy for the development- and technology-gap between industrialized and developing countries. Following its launching in 1980, GTZ-GATE chose biogas technology as a focal point of its activities. This resulted in a cross-sectoral scheme that has been accompanying and supporting the development and dissemination of biogas technology in Latin America, Asia and Africa.

Industrialized countries neither had sufficient experience nor appropriate technologies to build on in developing countries. Rather, this experience was identified in India and China and transmitted by a South-North-South transfer. The term 'appropriate technology' seemed justified by the fact that this technology was adapted to the respective local conditions during a 'learning-with-developing-countries' process.

A number of biogas dissemination programs involving German Technical Cooperation (GTZ) were launched in Bolivia, Colombia, Nicaragua, the Caribbean (see Belize and Jamaica), Tanzania, Kenya, Burundi, Morocco and Thailand. Initially, biogas and anaerobic technology focused on small scale farmers. At a later stage, larger farms as well as waste treatment issues increasingly became the focus of biogas technology.

These activities have resulted in a number of positive spin-off effects in the partner countries, in Germany, Europe and international development cooperation. Like in other fields of appropriate technology (AT) promotion, environmental protection, energy provision and the support to private enterprise development are increasingly seen as inseparable elements of sustainable (technology) development.

Outlook

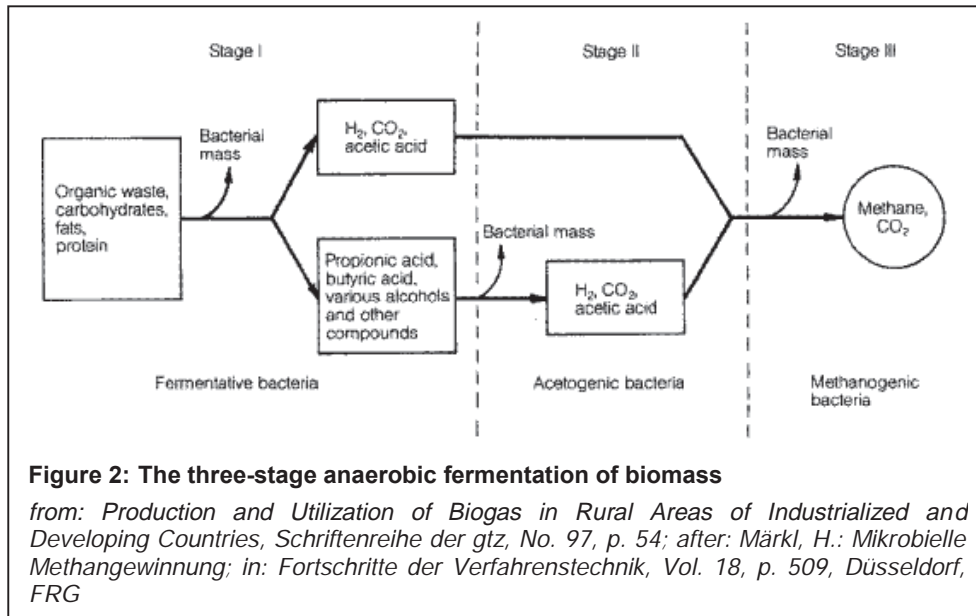
Today, the highest degree of market maturity can be found in the area of municipal sludge treatment, industrial wastewater purification and treatment of agricultural wastes. The use of the technology in municipal wastewater treatment is currently experiencing an upswing in Asia (India in particular) and Latin America. Anaerobic treatment of municipal organic waste is experiencing a boom in Northern Europe. Agricultural biogas plants in developing countries are usually promoted on a large scale in connection with energy and environmental issues, and are installed particularly where water pollution through liquid manure from agriculture is most severe.

The increasing emission of greenhouse gases, increasing water consumption and water pollution, declining soil fertility, unsatisfactory waste management and the growing rate of deforestation must be seen as parts of the unsustainable resource use systems that prevail worldwide. Biogas technology is one of the important hardware components in a chain of measures to counteract the above problems. GATE/ISAT is committed to play a lead role in networking and information exchange to ensure that the potential of biogas technology is recognized and made optimal use of.

Microbiology

The three steps of biogas production

Biogas microbes consist of a large group of complex and differently acting microbe species, notable the methane-producing bacteria. The whole biogas-process can be divided into three steps: hydrolysis, acidification, and methane formation (Figure 2). Three types of bacteria are involved (Figure 3).



Hydrolysis

In the first step (hydrolysis), the organic matter is enzymolyzed externally by extracellular enzymes (cellulase, amylase, protease and lipase) of microorganisms. Bacteria decompose the long chains of the complex carbohydrates, proteins and lipids into shorter parts. For example, polysaccharides are converted into monosaccharides. Proteins are split into peptides and amino acids.

Acidification

Acid-producing bacteria, involved in the second step, convert the intermediates of fermenting bacteria into acetic acid (CH_3COOH), hydrogen (H_2) and carbon dioxide (CO_2). These bacteria are facultatively anaerobic and can grow under acid conditions. To produce acetic acid, they need oxygen and carbon. For this, they use the oxygen solved in the solution or bounded-oxygen. Hereby, the acid-producing bacteria create an anaerobic condition which is essential for the methane producing microorganisms. Moreover, they reduce the compounds with a low molecular weight into alcohols, organic acids, amino acids, carbon dioxide, hydrogen sulphide and traces of methane. From a chemical standpoint, this process is partially endergonic (i.e. only possible with energy input), since bacteria alone are not capable of sustaining that type of reaction.

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Methane formation

Methane-producing bacteria, involved in the third step, decompose compounds with a low molecular weight. For example, they utilize hydrogen, carbon dioxide and acetic acid to form methane and carbon dioxide. Under natural conditions, methane producing microorganisms occur to the extent that anaerobic conditions are provided, e.g. under water (for example in marine sediments), in ruminant stomachs and in marshes. They are obligatory anaerobic and very sensitive to environmental changes. In contrast to the acidogenic and acetogenic bacteria, the methanogenic bacteria belong to the archaeobacter genus, i.e. to a group of bacteria with a very heterogeneous morphology and a number of common biochemical and molecular-biological properties that distinguish them from all other bacterial general. The main difference lies in the makeup of the bacteria's cell walls.

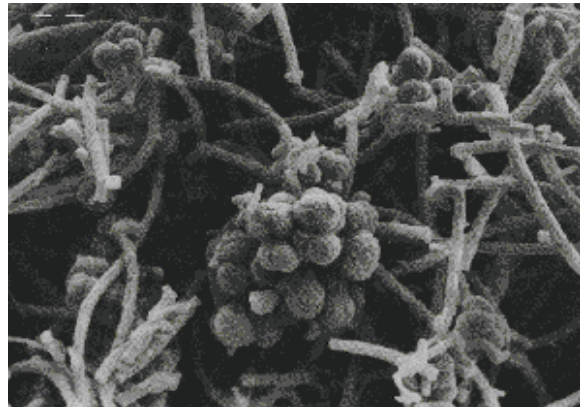


Figure 3: Various types of methanogenic bacteria. The spherically shaped bacteria are of the *methanosarcina* genus; the long, tubular ones are *methanothrix* bacteria, and the short, curved rods are bacteria that catabolize furfural and sulfates. The total length of the broken bar at top left, which serves as a size reference, corresponds to 1 micron.

Source: *Production and Utilization of Biogas in Rural Areas of Industrialized and Developing Countries*, Schriftenreihe der gtz, No. 97, p. 55

Symbiosis of bacteria

Methane- and acid-producing bacteria act in a symbiotical way. On the one hand, acid-producing bacteria create an atmosphere with ideal parameters for methane-producing bacteria (anaerobic conditions, compounds with a low molecular weight). On the other hand, methane-producing microorganisms use the intermediates of the acid-producing bacteria. Without consuming them, toxic conditions for the acid-producing microorganisms would develop.

In practical fermentation processes the metabolic actions of various bacteria all act in concert. No single bacteria is able to produce fermentation products alone.

Parameters and process optimisation

The metabolic activity involved in microbiological methanation is dependent on the following factors:

- Substrate temperature
- Available nutrients
- Retention time (flow-through time)
- pH level
- Nitrogen inhibition and C/N ratio
- Substrat solid content and agitation
- Inhibitory factors

Each of the various types of bacteria responsible for the three stages of the methanogenesis is affected differently by the above parameters. Since interactive effects between the various determining factors exist, no precise quantitative data on gas production as a function of the above factors are available. Thus, discussion of the various factors is limited to their qualitative effects on the process of fermentation.

Substrate temperature

Temperature range of anaerobic fermentation

Anaerobic fermentation is in principle possible between 3°C and approximately 70°C. Differentiation is generally made between three temperature ranges:

- The *psychrophilic temperature range* lies below 20°C,
- the *mesophilic temperature range* between 20°C and 40°C and
- the *thermophilic temperature range* above 40°C.

Minimal average temperature

The rate of bacteriological methane production increases with temperature. Since, however, the amount of free ammonia also increases with temperature, the bio-digestive performance could be inhibited or even reduced as a result. In general, unheated biogas plants perform satisfactory only where mean annual temperatures are around 20°C or above or where the average daily temperature is at least 18°C. Within the range of 20-28°C mean temperature, gas production increases over-proportionally. If the temperature of the bio-mass is below 15°C, gas production will be so low that the biogas plant is no longer economically feasible.

Changes in temperature

The process of bio-methanation is very sensitive to *changes* in temperature. The degree of sensitivity, in turn, is dependent on the temperature range. Brief fluctuations not exceeding the following limits may be regarded as still un-inhibitory with respect to the process of fermentation:

- psychrophilic range: $\pm 2^{\circ}\text{C/h}$
- mesophilic range: $\pm 1^{\circ}\text{C/h}$
- thermophilic range: $\pm 0,5^{\circ}\text{C/h}$

The temperature fluctuations between day and night are no great problem for plants built underground, since the temperature of the earth below a depth of one meter is practically constant.

Available nutrient

In order to grow, bacteria need more than just a supply of organic substances as a source of carbon and energy. They also require certain mineral nutrients. In addition to *carbon*, *oxygen* and *hydrogen*, the generation of bio-mass requires an adequate supply of *nitrogen*, *sulfur*,

phosphorous, potassium, calcium, magnesium and a number of trace elements such as *iron, manganese, molybdenum, zinc, cobalt, selenium, tungsten, nickel* etc. "Normal" substrates such as agricultural residues or municipal sewage usually contain adequate amounts of the mentioned elements. Higher concentration of any individual substance usually has an inhibitory effect, so that analyses are recommended on a case-to-case basis to determine which amount of which nutrients, if any, still needs to be added.

Retention time

Batch-type and continuous plants

The retention time can only be accurately defined in batch-type facilities. For continuous systems, the mean retention time is approximated by dividing the digester volume by the daily influent rate. Depending on the vessel geometry, the means of mixing, etc., the effective retention time may vary widely for the individual substrate constituents. Selection of a suitable retention time thus depends not only on the process temperature, but also on the type of substrate used.

Cost efficiency

Optimizing the process parameters *retention time - process temperature - substrate quality - volumetric load* determine, among others, the cost efficiency of the biological processes. But as each m³ digester volume has its price, heating equipment can be costly and high quality substrates may have alternative uses, the cost-benefit optimum in biogas production is almost always below the biological optimum.

Substrate

For liquid manure undergoing fermentation in the mesophilic temperature range, the following approximate values apply:

- liquid cow manure: 20-30 days
- liquid pig manure: 15-25 days
- liquid chicken manure: 20-40 days
- animal manure mixed with plant material: 50-80 days

If the retention time is too short, the bacteria in the digester are "washed out" faster than they can reproduce, so that the fermentation practically comes to a standstill. This problem rarely occurs in agricultural biogas systems.

pH value

The methane-producing bacteria live best under neutral to slightly alkaline conditions. Once the process of fermentation has stabilized under anaerobic conditions, the pH will normally take on a value of between 7 and 8.5. Due to the buffer effect of carbon dioxide-bicarbonate ($\text{CO}_2 - \text{HCO}_3^-$) and ammonia-ammonium ($\text{NH}_3 - \text{NH}_4^+$), the pH level is rarely taken as a measure of substrate acids and/or potential biogas yield. A digester containing a high volatile-acid concentration requires a somewhat higher-than-normal pH value. If the pH value drops below 6.2, the medium will have a toxic effect on the methanogenic bacteria.

Nitrogen inhibition and C/N ratio

Nitrogen inhibition

All substrates contain nitrogen. Tabelle 1 lists the nitrogen content of various organic substances and the C/N ratio. For higher pH values, even a relatively low nitrogen concentration may inhibit the process of fermentation. Noticeable inhibition occurs at a nitrogen concentration of roughly 1700 mg ammonium-nitrogen ($\text{NH}_4\text{-N}$) per liter substrate. Nonetheless, given enough time, the methanogens are capable of adapting to $\text{NH}_4\text{-N}$ concentrations in the range of 5000-7000 mg/l substrate, the main prerequisite being that the ammonia level (NH_3) does not exceed 200-300 mg $\text{NH}_3\text{-N}$ per liter substrate. The rate of

ammonia dissociation in water depends on the process temperature and ph value of the substrate slurry.

Table 1: Nitrogen-content and C/N-ratio data for a selection of substrates, compiled from various sources

Source	Biodegradable material	N in [%]	C/N
Maramba, Felix: Biogas and Waste Recycling - The Philippine Experience; Metro Manila, Phillipines, 1978, p. 43	A. Animal Dung		
	1. Hog	2.8	13.7
	2. Carabao	1.6	23.1
	3. Cow	1.8	19.9
	4. Chicken	3.7	9.65
	5. Duck	0.8	27.4
	6. Pugo	5.0	6.74
	Household Wastes		
	1. Nightsoil	7.1	6.72
	2. Kitchen waste	1.9	28.60
	C. Crop Residues (air-dry)		
	1. Corn stalks	1.2	56.6
	2. Rice straw	0.7	51.0
	3. Corn cobs	1.0	49.9
	4. Peanut hulls	1.7	31.0
	5. Cogon	1.07	-
	6. Bagasse	0.40	-
	D. Others		
	1. Kangkong	4.3	7.8
	2. Water lily	2.9	11.4
	3. Grass trimmings	2.5	15.7
Barnett, A. et al.: Biogas Technology in the Third World; Ottawa, Canada, 1978, p. 51	Night soil	6	6-10
	Cow manure	1.7	18
	Chicken manure	6.3	7.3
	Horse manure	2.3	25
	Hay, grass	4	12
	Hay, alfalfa	2.8	17
	Seaweed	1.9	79
	Oat straw	1.1	48
	Wheat straw	0.5	150
	Bagasse	0.3	150
	Sawdust	0.1	200-500
Kaltwasser, Bernd: Biogas; Wiesbaden, FRG, 1980, pp. 35-36	Night soil	6.0	5.9-10
	Cow manure	1.7	16.6-25
	Pig manure	3.8	6.2-12.5
	Chicken droppings	6.3	5-7.1
	Horse manure	2.3	25
	Sheep manure	3.8	33
	Hay	4.0	12.5-25
	Lucernes	2.8	16.6
	Algae	1.9	100
	Oat straw	1.1	50
	Wheat straw	0.5	100-125
	Cane trash (bagasse)	0.3	140
	Sawdust	0.1	200-500
	Cabbage	3.6	12.5
	Tomatoes	3.3	12.5
	Mustard (runch)	1.5	25
	Potato peels	1.5	25
	Rice straw	0.6	67
	Corn straw	0.8	50
	Fallen leaves	1.0	50
	Soybean stalks	1.3	33
	Peanut shoots	0.6	20

Source: Production and Utilization of Biogas in Rural Areas of Industrialized and Developing Countries, Schriftenreihe der gtz, No. 97, pp. 71-72

C/N ratio

Microorganisms need both nitrogen and carbon for assimilation into their cell structures. Various experiments have shown that the metabolic activity of methanogenic bacteria can be optimized at a C/N ratio of approximately 8-20, whereby the optimum point varies from case to case, depending on the nature of the substrate.

Substrate solids content and agitation

Substrate solids content

The mobility of the methanogens within the substrate is gradually impaired by an increasing solids content, and the biogas yield may suffer as a result. However, reports of relatively high biogas yields from landfill material with a high solids content may be found in recent literature. No generally valid guidelines can be offered with regard to specific biogas production for any particular solids percentage.

Agitation

Many substrates and various modes of fermentation require some sort of substrate agitation or mixing in order to maintain process stability within the digester. The most important objectives of agitation are:

- removal of the metabolites produced by the methanogens (gas)
- mixing of fresh substrate and bacterial population (inoculation)
- preclusion of scum formation and sedimentation
- avoidance of pronounced temperature gradients within the digester
- provision of a uniform bacterial population density
- prevention of the formation of dead spaces that would reduce the effective digester volume.

In selecting or designing a suitable means of agitation, the following points should be considered:

1. The process involves a symbiotic relationship between various strains of bacteria, i.e. the metabolite from one species can serve as nutrient for the next species, etc. Whenever the bacterial community is disrupted, the process of fermentation will remain more or less unproductive until an equivalent new community is formed. Consequently, excessive or too frequent mixing is usually detrimental to the process. Slow stirring is better than rapid agitation.
2. A thin layer of scum must not necessarily have an adverse effect on the process. For systems in which the digester is completely filled with substrate, so that any scum always remains sufficiently wet, there is little or no danger that the extraction of gas could be impeded by the scum.
3. Some types of biogas systems can function well without any mechanical agitation at all. Such systems are usually operated either on substrates with such a high solid content, that no stratification occurs, or on substrates consisting primarily of solute substances.

Since the results of agitation and mixing are highly dependent on the substrate in use, it is not possible to achieve a sufficiently uniform comparative evaluation of various mixing systems and/or intensity levels. Thus, each such system can only be designed on the basis of empirical data.

Inhibitory factors

The presence of heavy metals, antibiotics (Bacitracin, Flavomycin, Lasalocid, Monensin, Spiramycin, etc.) and detergents used in livestock husbandry can have an inhibitory effect on the process of bio-methanation. The following table (Tabelle 2) lists the limit concentrations (mg/l) for various inhibitors.

Substance	[mg/l]
Copper:	10-250
Calcium:	8000
Sodium:	8000
Magnesium:	3000
Nickel:	100-1000
Zinc:	350-1000
Chromium:	200-2000
Sulfide (as Sulfur):	200
Cyanide:	2

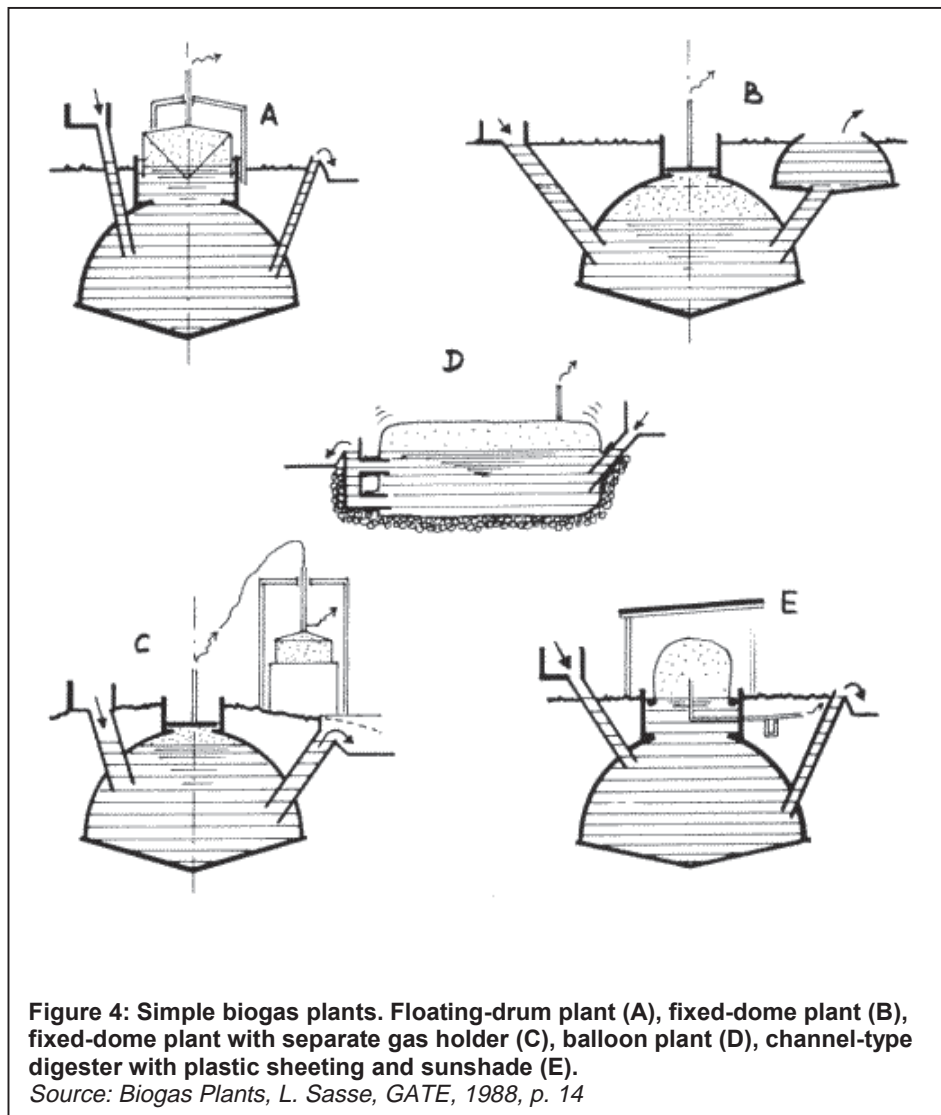
Table 2: Limiting concentrations for various inhibitors of biomethanation

The Physical Appearance of Different Types of Biogas Plants

The three main types of simple biogas plants are shown in Figure 4:

- balloon plants
- fixed-dome plants
- floating-drum plants

More information about the different types of biogas plants is provided under digester types.



Balloon plants

The balloon plant consists of a digester bag (e.g. PVC) in the upper part of which the gas is stored. The inlet and outlet are attached directly to the plastic skin of the balloon. The gas pressure is achieved through the elasticity of the balloon and by added weights placed on the balloon.

Advantages are low cost, ease of transportation, low construction sophistication, high digester temperatures, uncomplicated cleaning, emptying and maintenance.

Disadvantages can be the relatively short life span, high susceptibility to damage, little creation of local employment and, therefore, limited self-help potential.

A variation of the balloon plant is the **channel-type digester**, which is usually covered with plastic sheeting and a sunshade (Figure 4E). Balloon plants can be recommended wherever the balloon skin is not likely to be damaged and where the temperature is even and high.

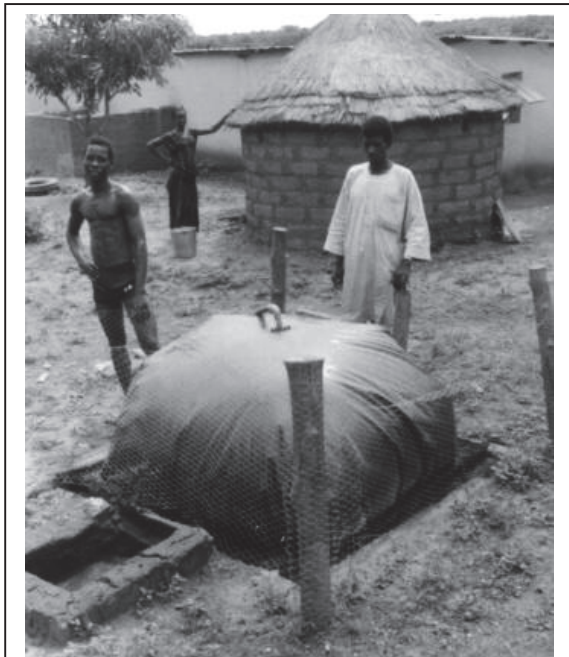


Figure 5: Small "foil-plant" (Ivory Coast)

Photo: Henning

Fixed-dome plants

The fixed-dome plant consists of a digester with a fixed, non-movable gas holder, which sits on top of the digester. When gas production starts, the slurry is displaced into the compensation tank. Gas pressure increases with the volume of gas stored and the height difference between the slurry level in the digester and the slurry level in the compensation tank.

Advantages are the relatively low construction costs, the absence of moving parts and rusting steel parts. If well constructed, fixed dome plants have a long life span. The underground construction saves space and protects the digester from temperature changes. The construction provides opportunities for skilled local employment.

Disadvantages are mainly the frequent problems with the gas-tightness of the brickwork gas holder (a small crack in the upper brickwork can cause heavy losses of biogas). Fixed-dome plants are, therefore, recommended only where construction can be supervised by experienced biogas technicians. The gas pressure fluctuates substantially depending on the volume of the stored gas. Even though the underground construction buffers temperature extremes, digester temperatures are generally low.

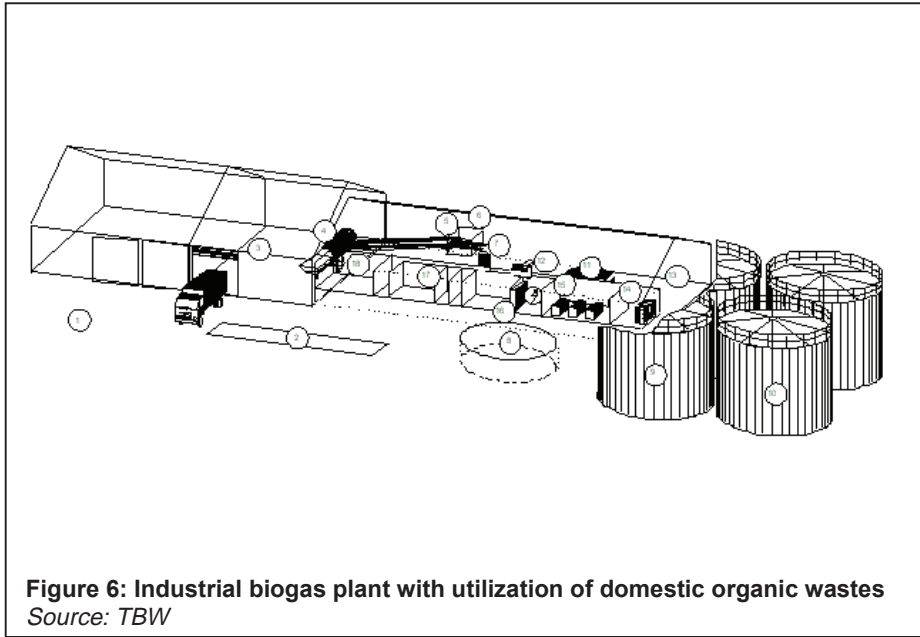
Floating-drum plants

Floating-drum plants consist of an underground digester and a moving gas-holder. The gas-holder floats either directly on the fermentation slurry or in a water jacket of its own. The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored. The gas drum is prevented from tilting by a guiding frame. If the drum floats in a water jacket, it cannot get stuck, even in substrate with high solid content.

Advantages are the simple, easily understood operation - the volume of stored gas is directly visible. The gas pressure is constant, determined by the weight of the gas holder. The construction is relatively easy, construction mistakes do not lead to major problems in operation and gas yield.

Disadvantages are high material costs of the steel drum, the susceptibility of steel parts to corrosion. Because of this, floating drum plants have a shorter life span than fixed-dome plants and regular maintenance costs for the painting of the drum.

To contrast these simple biogas plants, Figure 6 gives an impression about dimensions of industrial plants which are, for example, built in Europe.



Biogas Appliances

Biogas is a lean gas that can, in principle, be used like other fuel gas for household and industrial purposes, especially for:

- Gas cookers/stoves
- Biogas lamps
- Radiant heaters
- Incubators
- Refrigerators
- Engines

Gas cookers/stoves

Biogas cookers and stoves must meet various **basic requirements**:

- simple and easy operation
- versatility, e.g. for pots of various size, for cooking and broiling
- easy to clean
- acceptable cost and easy repair
- good burning properties, i.e. stable flame, high efficiency
- attractive appearance

Two-flame burners

A cooker is more than just a burner. It must satisfy certain aesthetic and utility requirements, which can vary widely from region to region. Thus, there is no such thing as an all-round biogas burner. Most households prefer two-flame burners. The burners should be set initially and then fixed. Efficiency will then remain at a high practical level. Single-flame burners and lightweight cook-stoves tend to be regarded as stop-gap solutions until more suitable alternatives can be afforded.

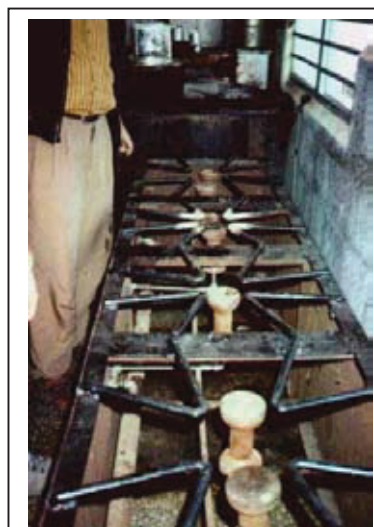


Figure 7: Institutional burner in a community kitchen
Photo: Krämer (TBW)

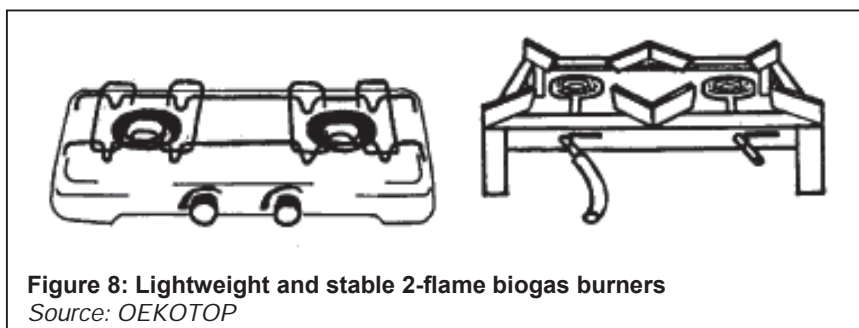


Figure 8: Lightweight and stable 2-flame biogas burners
Source: OEKOTOP

Biogas cookers require purposeful installation with adequate protection from the wind. Before any cooker is used, the burner must be carefully adjusted, i.e.:

- for a compact, bluish flame
- the pot should be cupped by the outer cone of the flame without being touched by the inner cone

- the flame should be self-stabilizing, i.e. flameless zones must re-ignite automatically within 2 to 3 seconds

Test measurements should be performed to optimize the burner setting and minimize consumption.



Figure 9: Biogas stove in China
Photo: Grosch (gtz/GATE)

Gas demand

The gas demand can be defined on the basis of energy consumed previously. For example, 1 kg firewood then corresponds to 200 l biogas, 1 kg dried cow dung corresponds to 100 l biogas and 1 kg charcoal corresponds to 500 l biogas.

The gas demand can also be defined using the daily cooking times. The gas consumption per person and meal lies between 150 and 300 liter biogas. For one liter water to be cooked 30-40 l biogas, for 1/2 kg rice 120-140 l and for 1/2 kg legumes 160-190 l are required.

Biogas lamps

Efficiency of biogas lamps

In villages without electricity, lighting is a basic need as well as a status symbol. However, biogas lamps are not very energy-efficient. This means that they also get very hot. The bright light of a biogas lamp is the result of incandescence, i.e. the intense heat-induced luminosity of special metals, so-called "rare earth" like thorium, cerium, lanthanum, etc. at temperatures of 1000-2000°C. If they hang directly below the roof, they cause a fire hazard. The mantles do not last long. It is important that the gas and air in a biogas lamp are thoroughly mixed before they reach the gas mantle, and that the air space around the mantle is adequately warm.

Light output

The light output (luminous flux) is measured in lumen (lm). At 400-500 lm, the maximum light-flux values that can be achieved with biogas lamps are comparable to those of a normal 25-75 W light bulb. Their luminous efficiency ranges from 1.2 to 2 lm/W. By comparison, the overall efficiency of a light bulb comes to 3-5 lm/W, and that of a fluorescent lamp ranges from 10 to 15 lm/W. One lamp consumes about 120-150 liter biogas per day.



Figure 10: Biogas lamp in Thailand
Photo: Kossmann (gtz/GATE)

Optimal tuning

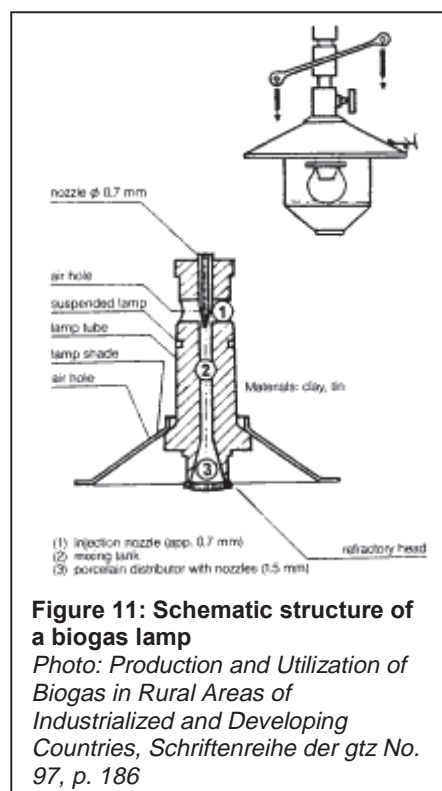
The performance of a biogas lamp is dependent on optimal tuning of the incandescent body (gas mantle) and the shape of the flame at the nozzle, i.e. the incandescent body must be surrounded by the inner (=hottest) core of the flame at the minimum gas consumption rate. If the incandescent body is too large, it will show dark spots; if the flame is too large, gas consumption will be too high for the light-flux yield. The lampshade reflects the light downward, and the glass prevents the loss of heat.

Shortcomings of commercial-type biogas lamps

Practical experience shows that commercial-type gas lamps are not optimally designed for the specific conditions of biogas combustion (fluctuating or low pressure, varying gas composition). The most frequently observed shortcomings are:

- excessively large nozzle diameters
- excessively large gas mantles
- no possibility of changing the injector
- poor or lacking means of combustion-air control

Such drawbacks result in unnecessarily high gas consumption and poor lighting. While the expert/extension officer has practically no influence on how a given lamp is designed, he can at least give due consideration to the mentioned aspects when it comes to selecting a particular model.



Adjusting a biogas lamp

Biogas lamps are controlled by adjusting the supply of gas and primary air. The aim is to make the gas mantle burn with uniform brightness and a steady, sputtering murmur (sound of burning, flowing biogas). To check the criteria, place the glass on the lamp and wait 2-5 minutes, until the lamp has reached its normal operating temperature. Most lamps operate at a gas pressure of 5-15 cm WC (water column). If the pressure is any lower, the mantle will not glow, and if the pressure is too high (fixed-dome plants) the mantle may tear.



Adjusting a biogas lamp requires two consecutive steps:

1. pre-control of the supply of biogas and primary air without the mantle, initially resulting in an elongated flame with a long inner core
2. fine adjustment with the incandescent body in place, resulting in a brightly glowing incandescent body, coupled with slight further adjustment of the air supply (usually more).

The adjustment is at its best when the dark portions of the incandescent body have just disappeared. A lux-meter can be used for objective control of the lamp adjustment.

Radiant heaters

Infrared heaters are used in agriculture for achieving the temperatures required for raising young stock, e.g. piglets and chicken in a limited amount of space. The nursery temperature for piglets begins at 30-35°C for the first week and then gradually drops off to an ambient temperature of 18-23°C in the 4th/5th week. As a rule, temperature control consists of raising or lowering the heater. Good ventilation is important in the stable / nursery in order to avoid excessive concentrations of CO or CO₂. Consequently, the animals must be kept under regular supervision, and the temperature must be checked at regular intervals. Heaters for pig or chicken rearing require some 200-300 l/h as a rule of thumb.

Thermal radiation of heaters

Radiant heaters develop their infrared thermal radiation via a ceramic body that is heated to 600-800°C (red-hot) by the biogas flame. The heating capacity of the radiant heater is defined by multiplying the gas flow by its net calorific value, since 95% of the biogas' energy content is converted to heat. Small-heater outputs range from 1.5 to 10 kW thermal power.

Gas pressure

Commercial-type heaters are designed for operating on butane, propane and natural gas at a supply pressure of between 30 and 80 mbar. Since the primary air supply is factory-set, converting a heater for biogas use normally consists of replacing the injector; experience shows that biogas heaters rarely work satisfactorily because the biogas has a low net calorific value and the gas supply pressure is below 20 mbar. The ceramic panel, therefore, is not adequately heated, i.e. the flame does not reach the entire surface, and the heater is very susceptible to draft.



Figure 14: Biogas radiant heater for raising piglets in Thailand
Photo: Kossmann (gtz/GATE)

Safety pilot and air filter

Biogas-fueled radiant heaters should always be equipped with a safety pilot, which turns off the gas supply if the temperatures goes low i.e. the biogas does not burn any longer. An air filter is required for sustained operation in dusty barns.

Incubators

Incubators are supposed to imitate and maintain optimal hatching temperatures for eggs. They are used to increase brooding efficiency.

Warm-water-heated planar-type incubators

Indirectly warm-water-heated planar-type incubators in which a burner heats water in a heating element for circulation through the incubating chamber are suitable for operating on biogas. The temperature is controlled by ether-cell-regulated vents.

Refrigerators

Absorption-type refrigerating machines operating on ammonia and water and equipped for automatic thermo-siphon circulation can be fuelled with biogas.

Burner

Since biogas is only the refrigerator's external source of heat, just the burner itself has to be modified. Whenever a refrigerator is converted for operating on biogas, care must be taken to ensure that all safety features (safety pilot) function properly. Remote ignition via a piezoelectric element substantially increases the ease of operation.

Gas demand

For 100 liters refrigeration volume, about 2000 l of biogas per day, depending on outside temperatures, must be assumed. A larger household refrigerator consumes about 3000 l per day.

Biogas-fueled engines

Gas demand

If the output of a biogas system is to be used for fueling engines, the plant must produce at least 10 m³ biogas per day. For example, to generate 1 kWh electricity with a generator, about 1 m³ biogas is required. Small-scale systems are therefore unsuitable as energy suppliers for engines.

Types of engines

The following types of engines are, in principle, well-suited for operating on biogas:

- Four-stroke diesel engines
- Four-stroke spark-ignition engines
- Converting diesel engines
- Converting spark-ignition engines

Four-stroke diesel engines:

A diesel engine draws air and compresses it at a ratio of 17:1 under a pressure of approximately 30-40 bar and a temperature of about 700°C. The injected fuel charge ignites itself. Power output is controlled by varying the injected amount of fuel, i.e. the air intake remains constant (so-called mixture control).

Four-stroke spark-ignition engines:

A spark-ignition engine (gasoline engine) draws a mixture of fuel (gasoline or gas) and the required amount of combustion air. The charge is ignited by a spark plug at a comparably low compression ratio of between 8:1 and 12:1. Power control is effected by varying the mixture intake via a throttle (so-called charge control).

Four-stroke diesel and spark-ignition engines are available in standard versions with power ratings ranging from 1 kW to more than 100 kW. Less suitable for biogas fueling are:

- loop-scavenging 2-stroke engines in which lubrication is achieved by adding oil to the liquid fuel, and
- large, slow-running (less than 1000 r.p.m) engines that are not built in large series, since they are accordingly expensive and require complicated control equipment.

Biogas engines are generally suitable for powering vehicles like tractors and light-duty trucks (pickups, vans). The fuel is contained in 200-bar steel cylinders (e.g. welding-gas cylinders). The technical, safety and energetic cost of gas compression, storage and filling is substantial enough to hinder large-scale application.

Converting diesel engines:

Diesel engines are designed for continuous operation (10000 or more operating hours). Basically, they are well-suited for conversion to biogas utilization according to either of two methods:

In the **dual fuel approach** the diesel engine remains extensively unmodified, except for the addition of a gas/air mixing chamber on the air-intake manifold (the air filter can be used as a mixing chamber). The injected diesel fuel still ignites itself, while the amount injected is automatically reduced by the speed governor, depending on how much biogas is injected into the mixing chamber. The biogas supply is controlled by hand. The maximum biogas intake must be kept below the point at which the engine begins to stutter. If that happens, the governor gets too much biogas and has turned down the diesel intake to an extent that ignition is no longer steady. Normally, 15-20% diesel is sufficient. As much as 80% of the diesel fuel can thus be replaced by biogas. Any lower share of biogas can also be used, since the governor automatically compensates with more diesel.

As a rule, dual-fuel diesels perform just as well as comparable engines operating on pure diesel. As in normal diesel operation, the speed is controlled by an accelerator lever, and load control is normally effected by hand, i.e. by adjusting the biogas valve (keeping in mind the maximum acceptable biogas intake level). In case of frequent power changes at steady speed, the biogas intake should be somewhat reduced to let the governor decrease the diesel intake without transgressing the minimum diesel intake. Thus, the speed is kept constant, even in case of power fluctuations. Important: No diesel engine should be subjected to air-side control.

While special T-pieces or mixing chambers with a volume of 50 to 100% of the engine cylinder volume can serve as the diesel / biogas mixing chamber, a proper mixing chamber offers the advantage of more thorough mixing.

To sum up, conversion according to the dual-fuel method is:

- a quick & easy do-it-yourself technique;
- able to accommodate an unsteady supply of biogas;
- well-suited for steady operation, since a single manual adjustment will suffice and
- requires a minimum share of diesel to ensure ignition

Conversion to Spark Ignition (Otto cycle) involves the following permanent modifications at the engine:

- removing the fuel-injection pump and nozzle
- adding an ignition distributor and an ignition coil with power supply (battery or dynamo)
- installing spark plugs in place of the injection nozzles
- adding a gas mixing valve or carburetor
- adding a throttle control device
- reducing the compression ratio (ratio of the maximum to the minimum volume of the space enclosed by the piston) to $\epsilon=11-12$
- observing the fact that, as a rule, engines with a pre-combustion or swirl chamber are not suitable for such conversion.

Converting a diesel engine to a biogas-fueled spark-ignition engine is expensive and complicated so that only pre-converted engines of that type should be procured.

Converting spark-ignition engines:

Converting a spark-ignition engine for biogas fueling requires replacement of the gasoline carburettor with a mixing valve (pressure-controlled venturi type or with throttle). The spark-ignition principle is retained, but should be advanced as necessary to account for slower combustion (approx. 5°-10° crankshaft angle) and to avoid overheating of the exhaust valve while precluding loss of energy due to still-combustible exhaust gases. The engine speed should be limited to 3000 rpm for the same reason. As in the case of diesel-engine

conversion, a simple mixing chamber should normally suffice for continuous operation at a steady speed. In addition, however, the mixing chamber should be equipped with a hand-operated air-side control valve for use in adjusting the air/fuel ratio (optimal "actual air volume/stoichiometric air volume" = 1.1).

Converting a spark-ignition engine results in a loss of performance amounting to as much as 30%. While partial compensation can be achieved by raising the compression ratio to $\epsilon=11-12$, such a measure also increases the mechanical and thermal load on the engine. Spark-ignition engines that are not explicitly marketed as suitable for running on gas or unleaded gasoline may suffer added wear & tear due to the absence of lead lubrication.

The speed control of converted spark-ignition engines is effected by way of a hand-operated throttle. Automatic speed control for different load conditions requires the addition of an electronic control device for the throttle.

The conversion of spark-ignition engines is evaluated as follows:

- Gasoline engines are readily available in the form of vehicle motors, but their useful life amounts to a mere 3000-4000 operating hours.
- The conversion effort essentially consists of adding a (well-turned) gas mixer.