DELIVERABLE II

BASELINE AND RESOURCE ASSESSMENT TO SUPPORT INDUSTRY SCALE BIOGAS PLANT IN TONGA

Part II: Report on biogas technologies

Client:

United Nations Industrial Development Organization (UNIDO)
Project: Tonga Circular Economy Project- Biogas Feasibility Study
REFERENCE NUMBER: 7000003978

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Gießen, Germany, January 25th 2021

AD Solutions UG (haftungsbeschränkt)

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Abbreviations

€	Euro	kW_{el}	Kilowatt electrical
°C	Degrees Celsius	kWh	Kilowatt hour
BOD_5	Biological oxygen demand in 5 days	kWh/m^3	Kilowatt hour per cubic metre
C	Carbon	l	Litre
CH_4	Methane	m^3	Cubic metre
CHP	Combined heat and power	$m^3/h\ CH_4$	Cubic metre of methane per hour
cm	Centimetre	mg	Milligram
CO_2	Carbon dioxide	mg/l	Milligram per litre
COD	Chemical oxygen demand	mm	Millimetre
CSTR	Complete stirred tank reactor	MW	Megawatt
DM	Dry matter	MW_{el}	Megawatt electrical
DWA	German association for Water, Wastewater and Waste	N	Nitrogen
e.g.	For example	n/a	Not available/Not applicable
etc.	Et cetera	Nm^3	Norm cubic metre
FM	Fresh matter	O & M	Operations and maintenance
FNR	Agency for renewable resources	OLR	Organic loading rate
FOG	Fat, oil and grease	PE	Population equivalent
h	Hour	ppm	Parts per million
H_2	Hydrogen	SO_x	Sulphur oxides
H_2S	Hydrogen sulphide	T	Metric tonne
HDPE	High density polyethylene	t/a	Metric tonne per annum
K	Kelvin	tFM	Metric tonne fresh matter
kg_{VS}/m^3	Kilogram volatile solids per cubic metre	TS/l	Total solids per litre
kW	Kilowatt	TSS	Total suspended solids

1 Objective of this report

The aim of this report is to provide an overview of different types of biogas technologies, which might be suitable for the theoretical biomass potential available at Tongatapu (see Report WP 1), Kingdom of Tonga[1]. Hence, several state-of-the-art technologies for biogas utilization are already short-listed and described, based on latest international experience. The pre-selected biogas technologies could be relevant for the Tongan market and suit its special conditions and barriers such as extreme weather situations (e.g., strong storms) and its limited availability of industrial scale biogas technologies and associated service supply chains. Selection criteria include maturity of technology, its international dissemination, energy (and by-product) generation performance, process stability, required after-care service (e.g. maintenance), and physical robustness.

2 The Process of Biogas Production

This chapter provides a general overview on the process of biogas production.

2.1 Basics of Biogas Production

The process of biogas production is an anaerobic microbiological decomposition transforming complex organic substrates into a mixture of gas. This mixture mainly consists of methane (CH4) and carbon dioxide (CO2) as well a small proportion of trace elements (see figure 1).

Methane concentration and subsequent calorific value of biogas is subject to substrate composition and varies between 5 and 7.5 kWh/m^3. This corresponds to about half a litre of diesel oil. Net electrical and calorific value depends on the efficiency of a co-generation unit or any other technical equipment utilising produced biogas. Methane is a valuable component under the aspect of using biogas as a fuel.

[1] A detailed technical anaylsis of the most suitable biogas technology for the available input substrate is subject to report of deliverable III.

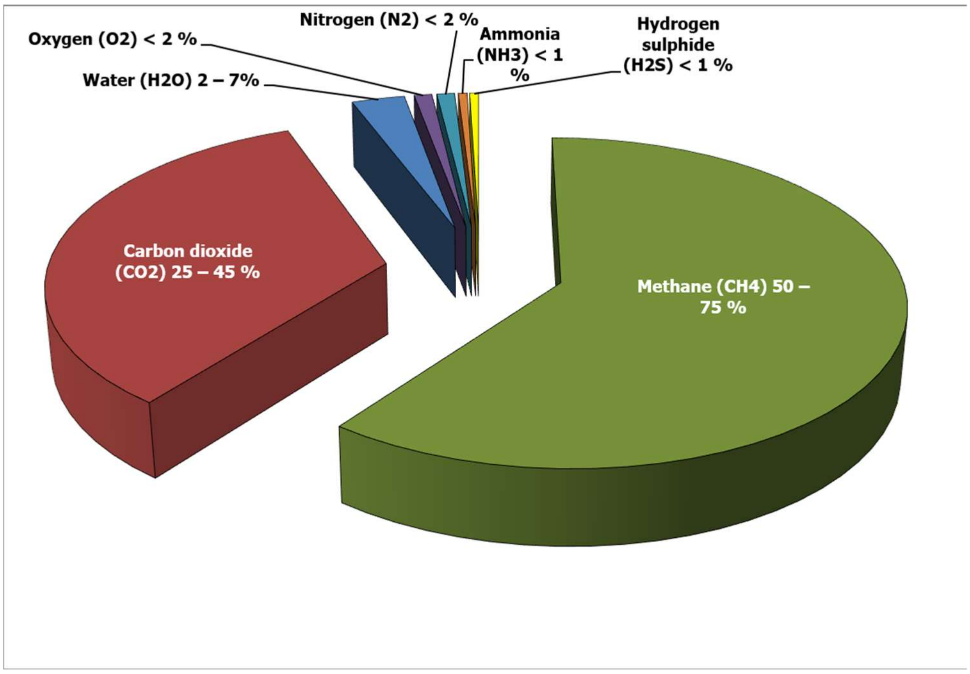

Figure 1: Components of biogas

Biogas can be basically produced from any organic substrate. Nowadays, the economically attractive input substrates are livestock manure, crop (e.g. corn or sorghum), green cuttings, leftovers of the food or agricultural industry and others. These substrates partly consist of complex organic matters such as carbohydrates, fats and proteins.

The microorganisms decomposing organic matter into biogas are dependent on an anaerobic milieu, meaning the absence of oxygen. The most important parameters for characterizing the proportion of organic matter in the substrate are dry matter content (DM) and volatile solids content (VS), whereby the VS proportion is in relation to the proportion of organic substance in the substrate.

To methanogenic bacteria even small amounts of oxygen are critically dangerous. Nevertheless, it is not possible to completely avoid oxygenation into a digester. Reason for the processes are not inhibited or completely stopped is that all stages of the biogas process are taking place at the same time and some bacteria, especially hydrolytic bacteria are facultative anaerobic. This means that these bacteria can, if there is only a limited quantity of oxygen inside the system, consume the oxygen before it inhibits or damages other bacteria.

2.2 Temperature

During chemical processes, a higher ambience temperature generally accelerates the performance. This can be applied to biological reactions only to a certain extent. It has to be kept in mind, that the involved microorganisms have different optimum temperatures. Is the optimum temperature exceeded or the temperature falls below a minimal value; inhibition occurs. Extreme temperatures can even damage the system irreparably. According to their optimum temperature the anaerobic microorganisms can be divided into three groups:

- Psychrophilic bacteria have an optimum temperature below 25°C. Is the biogas plant operated within this temperature range, heating of the digesters or the substrate is not needed. Although this temperature level is technically the most basic ones, as it does seldom require an external heating of the fermenter unit, the main disadvantage is a very poor gas production and decomposition.
- Mesophilic bacteria have their optimum temperature in the range of 37 – 42°C. Within this temperature range an improved gas yield and high process stability can be reached, which is the reason for the wide dissemination of mesophilic operation.
- Thermophilic bacteria operate best in temperatures between 50 – 60°C. These high temperatures lead to an accelerated decomposition of organic matter. Disadvantages are a higher demand of energy and likeliness to process disruption.

Experience has shown that transitions between temperatures are floating. Sudden changes of temperature can damage the microorganisms, while microorganisms can adapt to slowly changing new temperature environment.

Although the mesophilic temperature range would be preferred for the project due to the process paired with relatively high system efficiency, it needs to be stated that even at Tongatapu with its annual ambient temperature range an additional heating and insulation would be required to maintain a constant temperature within the reactor.

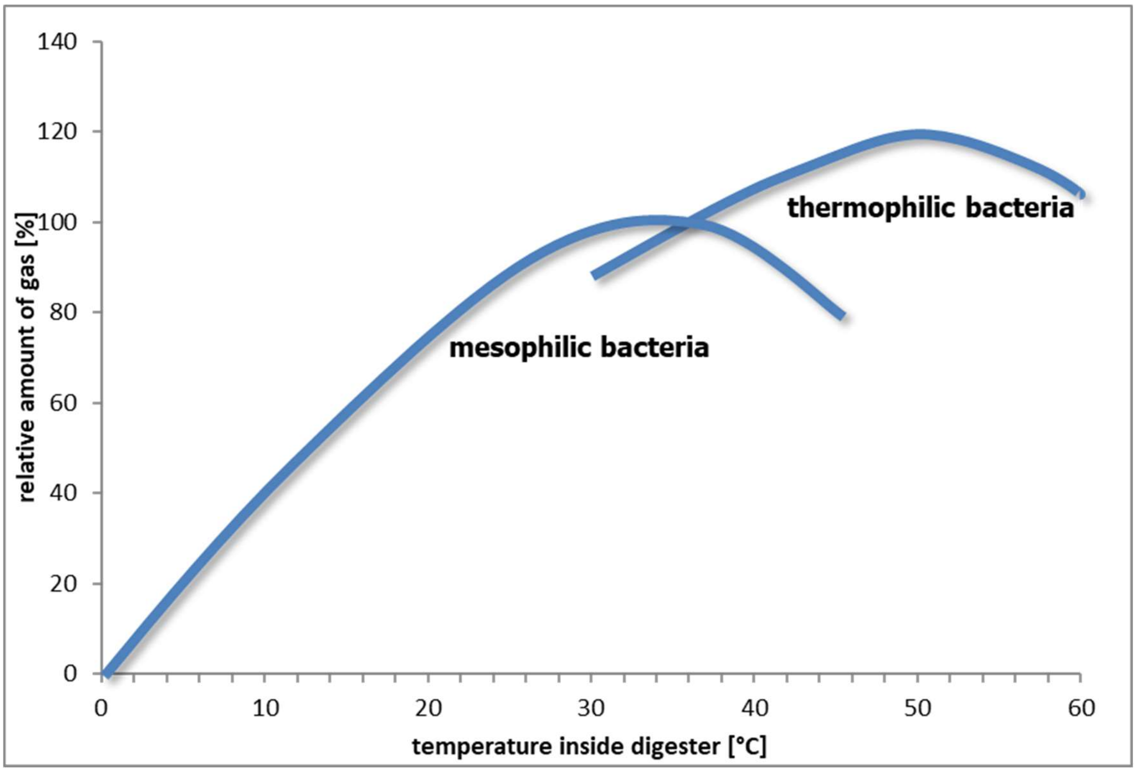

Figure 2: Temperature effect on bacteria

2.3 pH-value

The pH-value is also of great relevance to the biogas process. Due to alkaline and acidic metabolic products, the pH automatically adjusts inside a digester to a certain extent. This automatic adjustment can be disturbed though. For example, in case the methane production is inhibited, or too much organic matter is fed into the digester, acidic metabolic products are enriched inside the system. This can lead to a chain reaction inhibiting the whole process.

Because of its inertia the pH value has only a limited use for process control; still it should be measured on a regular basis to control the pH value remains in the neutral range 7 – 8.

2.4 Inhibiting Substances

The inhibition of gas production or biological processes can have diverse causes. Inhibition can evolve either from operational mistakes or inhibiting substances feed into the digester can be the cause for the decrease of biological activities, thus decrease of biogas production. These substances can, in small concentration, slow down the biological process or in higher toxic concentration even completely break it down. The two most abundant inhibitors are described below, both are intermediates of the anaerobic process.

2.4.1 Ammonia

The digester's content of ammonia is resulting from the nitrogen concentration of inlet substrates as well as the decomposition of organic nitrogen compounds (mainly proteins). For most microorganism's ammonia and ammonium serve as source of nitrogen. However, above a certain concentration, inhibition occurs during the anaerobic process.

In water, free ammonia (NH3) will change into ammonium (NH4+) and therefore will become chemically balanced.

$$NH_3 + H_2O \Leftrightarrow NH_4^+ + OH^-$$

This chemical balance is influenced by pH and temperature. The inhibiting or toxic effect evolves from undissociated ammonia (NH3). At concentrations of 1,500 – 3,000 mg/l NH4+ and a pH below 7,4 no inhibition is to be expected. The toxicity of ammonia is not only a result of its absolute concentration, but also of the adaption time. Is the adaption time long enough, a higher ammonia concentration is possibly not effecting the processes.

2.4.2 Organic Acids

One potential inhibitor evolving during the decomposition of complex organic substrate mixtures are short chain organic fatty acids. High concentrations of these organic acids, especially acetic acid and propionic acid can be cause for inhibition of the processes. During a well working fermentation the concentration of volatile fatty acids is mostly below 1,000 mg/l. The effects of volatile organic acids are, similar to the increasing ammonia concentration, connected to the time available for adaption.

2.5 Dry matter (DM) content

There are different types of biogas systems (Figure 3) for treatment of organic substrates. Depending on the possibility to control the temperature in the fermenter and especially the mixing technology applied in the given system, determine which range of dry matter (DM) can be treated.

Biogas systems are divided into wet and dry fermentation. Wet fermentation refers to anaerobic treatment of wet substrate with DM content of less than 25%, whereby the substrate becomes pumpable and mixable during fermentation. Dry fermentation describes anaerobic treatment of substrate with DM content of more than 25% that remains stackable throughout the whole process.

In general, the higher the temperature and the more efficiently stirred, the higher the DM content that can be treated. The only exception to this is the garage type fermenter (see chapter 3.1.3).

2.6 Organic Loading Rate (O_{LR})

The organic loading rate indicates the maximum amount of volatile solids (VS) per cubic meter digester volume to be fed per day without overfeeding the bacteria and therefore endangering the process. The optimized organic loading rate depends mainly on input substrate and the process temperature. It is calculated by using VS content, volume of daily fed substrates and the digester volume. An average organic loading rate under mesophilic ambience (38°C process temperature) varies from 2 – 5 kgVS/m^3*d, feeding a daily amount of volatile solids of 2 to 5 kg per m^3 of digester volume into the digester. In practice most biogas digesters are being operated with an O_{LR} of approx. 3 kgVS/m^3*d.

2.7 Hydraulic retention time (H_{RT})

The hydraulic retention time is the durance a feed substrate is theoretically inside the digester until being discharged. It is calculated by putting the digester volume in relation with the volume of daily fed substrate.

Hydraulic retention time, H_{RT} [d]

$$H_{RT} = \frac{V_{Digester}[m3]}{V_{Substrate}[m3/d]}$$

2.8 Feeding of substrates

To avoid overfeeding and too high loading charges, it is useful feed the digester with small batches and in short intervals, rather than in one big batch. This is valid as well for the main substrate (e.g. manure) as for co-substrates (e.g. food leftovers). The feeding in small even charges also guarantees constant temperatures inside the digester. Thus, all biogas systems evaluated should be fed as continuously as possible with the exception of the garage type fermenter (see chapter 3.1.3).

2.9 Agitation

To reach high gas production rates, the microorganisms and the substrates have to be mixed thoroughly. In almost all biogas plants for the treatment of sludge or solid substrates it is guaranteed by operating multiple types of agitation systems.

Mixing is important to prevent phase separation inside digesters. Usually, the substrate has a lower density than the decomposing microorganisms and therefor tends to build flotation layers, while in lower regions of an unmixed digester settlements can be observed. Flotation layers can become very compact and develop thicknesses of double-digit cm and hinder gas emanation. Another aspect is to distribute the needed temperature evenly in the system.

On the other hand, it is important not to mix a digester too extreme, because some of the microorganisms build symbiosis with one another which can be disturbed by high shearing forces.

Thus, it is necessary to find a compromise between complete mixing and limiting shearing forces, this is best be reached by using slowly rotation agitators or mixing in short intervals. For economic reasons, the time of agitators operating should be as short as possible.

2.10 Benefits of Biogas Technology

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

- Stabilisation and reduction of organic load of organic residues (livestock manure, agricultural by-products, organic farming residues, etc.)
- Production of electrical and thermal (heat and/or cold) energy
- Transformation of organic waste into high quality fertiliser
- Disinfection through reduction of pathogens, worm eggs and flies
- Environmental advantages through the protection of soil, water and air due to fossil fuel switch
- Reducing pressure on landfill sites
- Additional income for farmers through energy and fertiliser production
- Macro-economic benefits through decentralised energy generation and environmental protection

3 Proven technologies for anaerobic digestion and biogas utilisation

3.1 Different types of biogas systems

As mentioned above, various types of potential biogas substrates with different characteristics (substrates can be solid, pasty or liquid, with a high organic content or low one, etc.) can be treated in a biogas plant. Different types of biogas systems for different conditions have been developed over the past decades. While some are adaptations of simple earth ponds, others are highly sophisticated industrial plants.

The evaluation of substrates available in Tongatapu (deliverable II – part 1 - Report on resource availability and sustainability) determined that both sludge and solid substrates needs to be treated in order to produce the minimum expected capacity of electrical energy (0.5 MW). Therefore, only technologies that can also treat sludge and solid substrates are considered in this report.

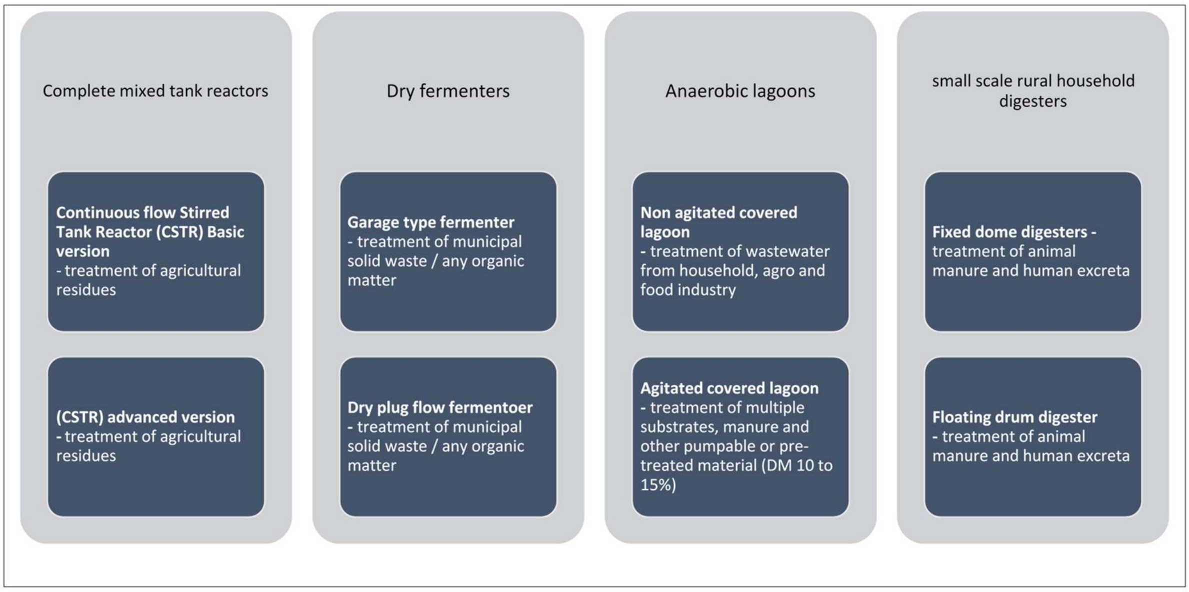

Figure 3: Types of biogas systems evaluated

All systems have in common that in an enclosed vessel (tank, lagoon, garage or pit), biogas is produced by specialised bacteria, which can then be used to substitute other fuels. Since a biogas system must be fed in certain intervals, ranging from several times per day to once every few weeks (discontinuous feeding as e.g., garage type fermenter) before the substrate is treated in this vessel, it needs to be stored nearby. Hence, all biogas systems have storing facilities; these can be tanks and lagoons for liquid substrates or silos and covered areas for solid substrates. Digestate (treated sludge after anaerobic treatment) also needs to be stored before it is applied to agricultural areas or further processed. The digestate is usually stored in a tank or lagoon connected to the digester.

Continuous Flow Stirred Tank Reactor (CSTR) is a widely applied state-of-the-art technology design for the digestion of substrates with a dry matter (DM) content of 10 to 15%, which can be considered as pumpable and mixable substrates. CSTR is usually considered for the treatment of agricultural substrates, especially manure, where the design and equipment could be kept relatively simple. CSTR is also used in the food industry and to a limited extent for municipal organic waste. For the treatment of more complex substrates with a higher degree of decomposition, more sophisticated designs, equipment, and monitoring are required (see chapters 3.1.1 and 3.1.2).

Dry fermenters are specially developed for the treatment of large quantities of municipal waste, but principally are suitable for all substrates with increased DM content. They are divided into continuous and discontinuous systems. Discontinuous container systems are suited for substrates with DM concentrations of 35 to 50% and can bear high fractions of impurities (see chapter 3.1.3). Continuous systems work with DM contents of up to 35% and use either horizontal reactors in which the substrate is agitated via mixers (plug flow) or vertically erected reactors in which mixing is performed by a pumping system (see chapter 3.1.4).

In many countries, anaerobic lagoons are the common method of treatment for substrates such as agricultural (manure), or liquid agro-industrial waste streams (dairy industry and meat industry) and municipal wastewater treatment sectors. The vast majority of these several thousand lagoons have neither any mixing technology nor a heating system. A few are more sophisticated applying mixing and/or heating technology to improve efficiency and durability considerably.

3.1.1 Continuous flow Stirred Tank Reactor (CSTR), basic version

For the treatment of agricultural residues inside a CSTR, there are multiple possibilities concerning its configurations and components, which enable diverse combinations. Figure 4. visualizes a typical CSTR.

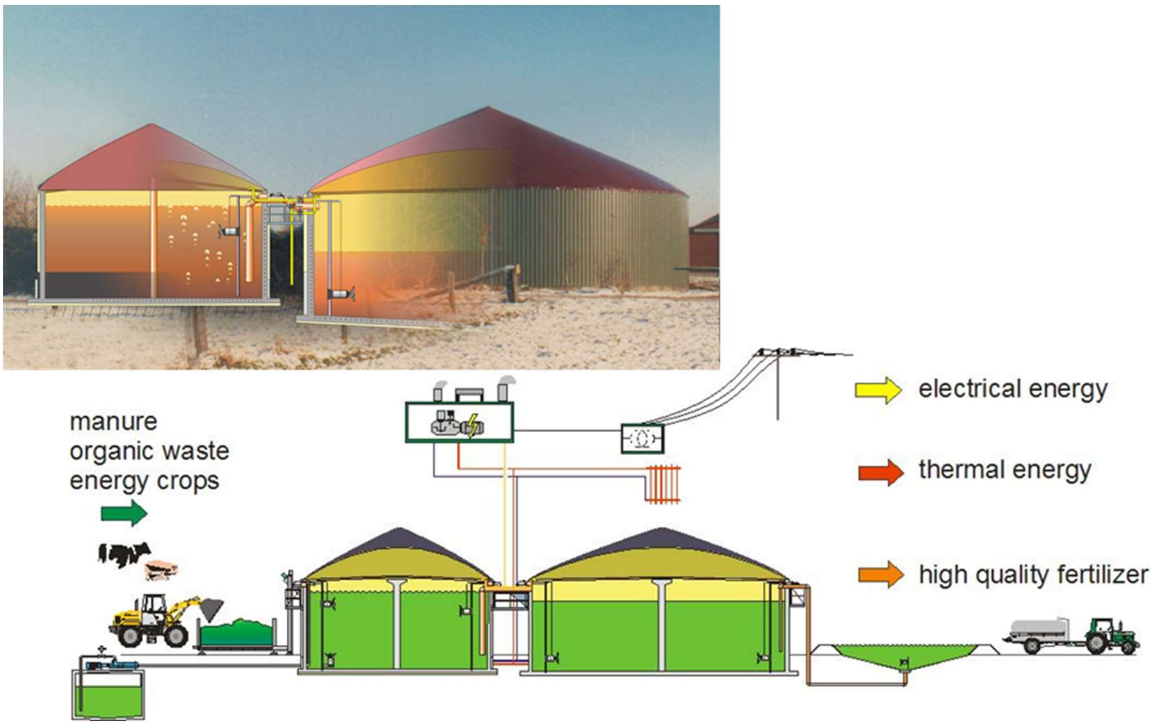

Figure 4: CSTR plant, basic (source Biogas Nord GmbH)

PRE-TREATMENT OF SUBSTRATES:

Substrates that are not pumpable should be macerated and diluted with water or digestate of the operating system. Generally, it can be said that substrates with a dry matter content of 10 to 15% are suitable.

CONSTRUCTION AND EQUIPMENT:

For economic reasons, the typical design of digesters treating agricultural residues are usually flatly (up to 7 to 8m) built tanks with a large diameter, laterally equipped with agitators and gas storage which is affixed to the top of the tank. Digesters with a reversed ratio between height and diameter have a higher specific investment cost.

For larger reactors, the cover must be built as a double membrane system (usually air supported) for safety reasons concerning wind and snow loads. For smaller tanks or tanks located in areas protected from the effects of winds, single membrane gas storages are sufficient to store produced biogas. In double membrane gas storage roofs, the actual storage is between the inner membrane, and the outer membrane serves as a weather protection mechanism and constantly needs to be firmly strained by air blowers.

To guarantee optimum conditions for the biological processes, the system should be operated under mesophilic (35°C to 40°C) or thermophilic (52°C to 55°C) temperature conditions. Insulating the tank's walls to minimise heat losses or uncontrolled rise of temperature, and the installation of an internal heating system or external heat exchanger guarantees a stable process temperature. Usually, excess heat of a combined heat and power (CHP) unit is used for this purpose.

Smaller plants and ones treating manure as the only (mono) substrate are equipped with only little instrumentation and control equipment. For example, instead of pneumatic valves operated from a central control station, manually operated valves are installed (all valves should be redundant for operational safety). Existing manure tanks can be used for digestate storage.

EFFICIENCY:

CSTRs fed with agricultural substrates are usually operated at organic loading (O_{LR}) rates between 2 and 4 kg_{VS}/m^3 digester volume. During plant layout, the configuration of equipment needs to take this into account and be adapted to operational conditions. Biogas production is a direct result of input material, it varies between approximately 0,7 to > 3,0 m^3 biogas per m^3 digester volume and day.

COSTS:

Investment costs are strongly related to plant size, used substrates, required substrate/digestate storages, required pre-treatment, the built-in equipment and its technical realisation and therefore cannot be estimated. Operational costs could estimated at 2% to 3% of the investment costs annually plus the operational costs of the CHP as specified in chapter 3.2.2.

ADVANTAGES:

- Economic robust and flexible technology
- Processing of different types of organic waste mixtures
- Independence of commodities
- Intensifying possible livestock activity
- Transferring organic waste into fertiliser

DISADVANTAGES:

- Requirement of constant substrate supply to justify investment and operation costs
- Trained operating staff required
- Regular technical service required for key equipment
- Seasonality in agricultural production
- Competition for agricultural land and other use

3.1.2 Continuous Flow Stirred Tank Reactor (CSTR), advanced version

CSTR fermentation of residues produced by the processing industry usually demands a more sophisticated fixture and furnishing of the installations in comparison to agriculture substrates. For these input materials, digester tanks with a fixed roof and central agitator are often used (see Figure 5). Major differences compared to basic CSTRs are improved flow characteristics and limited shearing forces inside the reactor. This type of reactor requires higher investments, since the tank's static is required to bear the agitator's forces, and external gas storage is required.

Figure 5: CSTR plant, advanced (source: Krieg+Fischer GmbH)

PRE-TREATMENT OF SUBSTRATES:

The same requirements for CSTR basic version apply here.

CONSTRUCTION AND EQUIPMENT:

For larger plants or plants treating more complex substrates, high reactors in which the agitation equipment makes the biggest difference, are usually used. Figure 5 shows two identical primary digesters, each one equipped with a concentric central agitator and fixed steel roof. This construction allows for ideal mixing at a relatively slow agitation speed. The position of the engine, which is located outside the tank, provides for easier maintenance and avoids corrosion of the engine.

Further installations are a direct result of treated substrates and follow the ones indicated in the CSTR basic chapter. The higher the proportion of quickly treatable substrates, the more instrumentation and control equipment is necessary. Substrates with high fibre content need to be considered during the planning process. Insulating the reactor and heating the substrate is required for an increased biological efficiency, especially if operated under thermophilic temperatures.

EFFICIENCY:

With adequate instrumentation and control equipment, organic loading rates up to $7kg_{VS}/m^3$digester volume are possible. Gas production ranges between 0,7 to > $6m^3$ biogas/m^3 digester volume per day.

COSTS:

Compared to CSTR basic version, the investment cost is higher, because the digester technology is more sophisticated. Nevertheless, the economic performance is generally better because of a higher gas production rate and a relatively lower on-site power demand.

ADVANTAGES:

- Improved flow characteristics and limited shearing forces inside the reactor (compared to CSTR basic version)
- Improved energy utilisation and emission reduction
- Auto consumption of energy and fuel and other synergies with industry and agriculture (reuse of treated substrates)

DISADVANTAGES:

- Higher investment costs (compared to CSTR basic version)
- Operation and maintenance are more extensive than for CSTR basic version
- Requirement of constant substrate supply to justify investment and operation costs
- Regular technical service required for key equipment
- Seasonality in agricultural production

3.1.3 Garage or pit digesters

Discontinuous dry-fermentation process (batch process) in so-called garage or pit fermenters require less efforts for the substrate preparation. The substrate may consist of relatively large pieces and is inserted into the fermenter with loaders. To inoculate the fermentation process, mixing of fresh substrate with digestate from the previous cycle is required (minimum ratio 1:1). The machinery is burdened by this procedure (either by rough parts, heavy or light fabrics and wood-like loading constituents' contaminants), and the process engineering outlay for the homogenisation and mixing of the material is reduced to a minimum (static mixture by loaders).

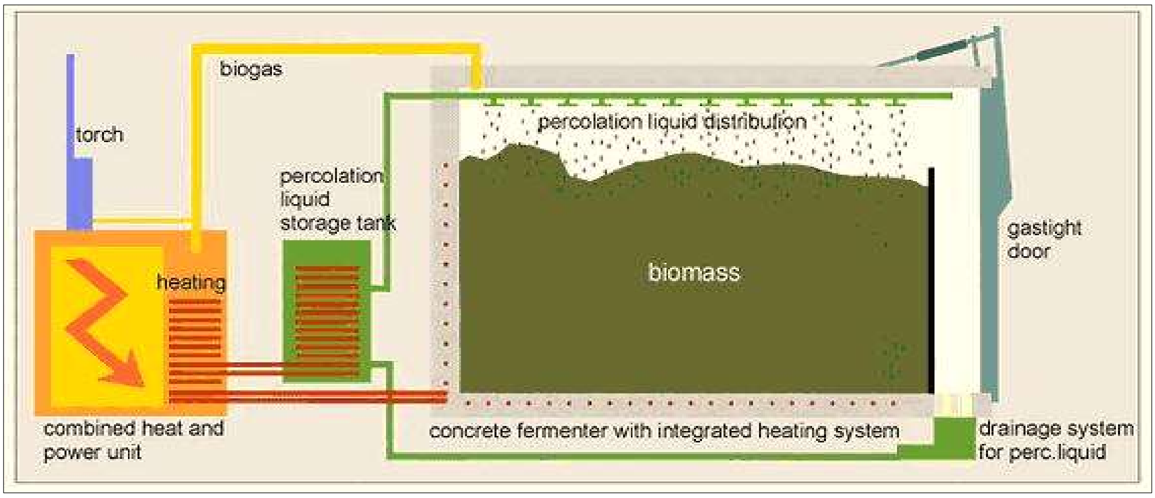

Figure 6: Discontinuous dry-digester (source: Bekon)

PRE-TREATMENT OF SUBSTRATES:

Other than a coarse crushing of the fresh substrate, a thorough mixing with a certain proportion (up to 30%) of already treated substrate is required. This is done after removing treated substrate and before inserting fresh one. Usually, a wheel loader mixes the two components outside the digester.

CONSTRUCTION AND EQUIPMENT:

The planned throughput dictates the number of garage digesters, since each garage requires a treatment cycle of 3 to 6 weeks. These garages are gas-tight and connected to an external gas storage. To provide optimal living conditions for the biogas producing micro-organisms, the substrate is sprinkled with recycled process liquid (percolate), which is buffered in a separate tank (Figure 6). A heating system, installed inside the walls, provides required temperatures (mesophilic, thermophilic). After finalising one digesting batch, the box is actively aerated to avoid methane emissions after opening the box. The digestate is partly used to inoculate a new batch and partly sent to a rotting facility. After the completion of a fermentation cycle, the garage is actively aerated.

EFFICIENCY:

Due to discontinuous process operations, limited pre-treatment and agitation of treated substrate, there is comparably little gas production. This is further compounded by losses during opening of the digester. When compared to continuously operated systems, this discontinuous treatment has 20 to 30% lower biogas production.

COSTS:

The investment cost for discontinuous treatment is lower than for continuous treatment because the costs for pre-treatment and digester technology are reduced (e.g. no agitators). Operational costs for discontinuous treatment are higher, however, because of the intensity of wheel-loader operation, and larger substrate volumes (fresh material and digestate). Lower gas production also lowers the income.

ADVANTAGES:

- Energy utilisation of municipal solid waste with little pre-treatment
- Reducing emissions
- Initial investment for the plant is relatively low
- Reduction in landfill disposal in the case of treatment of previously landfilled waste

DISADVANTAGES:

- Logistics are challenging for larger plants (loading and unloading garages)
- Low biogas production rate

3.1.4 Plug-flow digester or horizontal dry-fermentation digester

This system of dry-fermentation works continuously. Here the same volume of digestate, compared to fresh substrate, is removed during or after feeding. The most common continuous dry-fermentation digesters are plug-flow digester or horizontal dry-fermentation digester (Figure 7) using slow speed agitators with large capacity.

Alternatively, vertically digesters can be applied with feeding at the top and extraction through a conical outlet at the bottom. This digester system operates without mechanical agitators but with intensive recirculation of the digestate to generate a proper mixing with low energy demand (Figure 8).

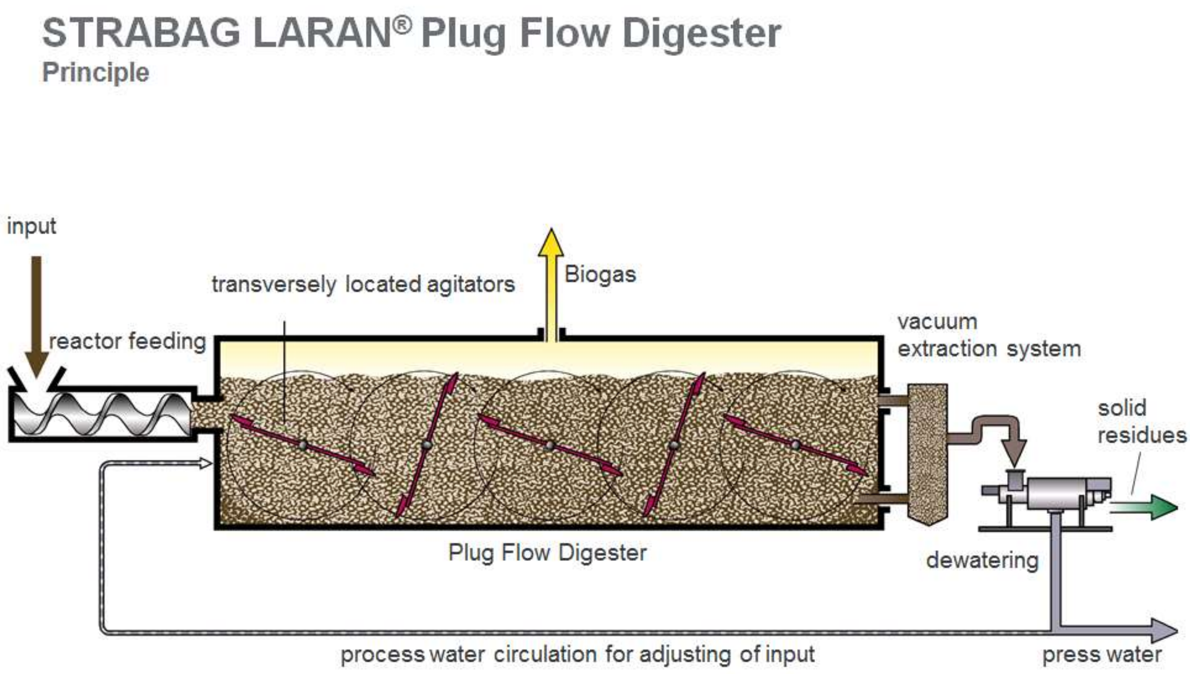

Figure 7: Continuous plug-flow dry-digester (Source: www.strabag-umwelttechnik.com)

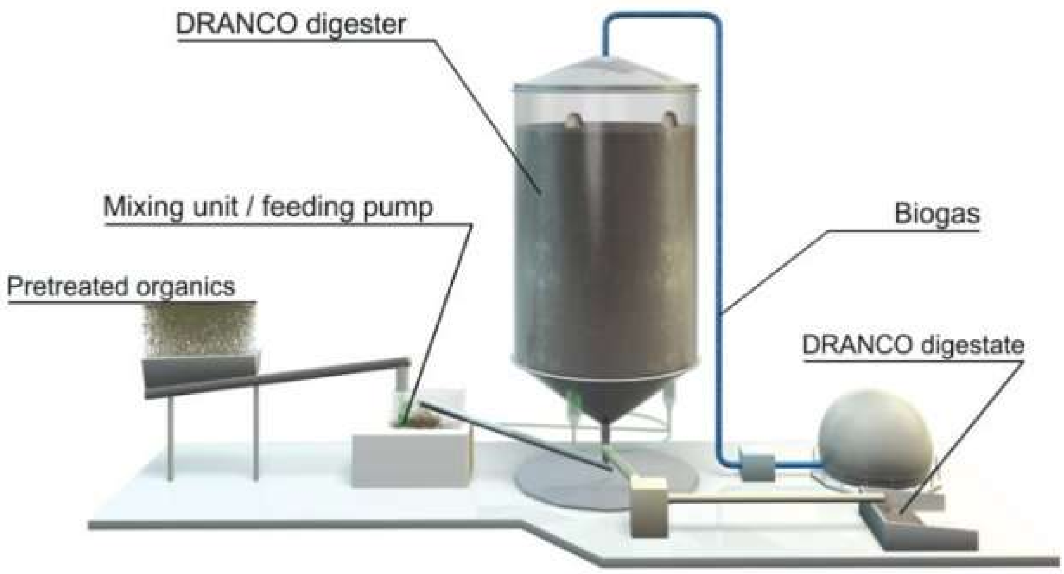

Figure 8: Continuous vertical dry-digester (Source: www.energy-xprt.com)

PRE-TREATMENT OF SUBSTRATES:

Pre-treatment of substrates to be suitable for continuous dry-fermentation is necessary in the form of crushing and sieving (<40mm to 60mm) of the raw material. Furthermore, impurities (e.g. metals) should be removed. The dry matter content should not exceed 45%.

CONSTRUCTION AND EQUIPMENT:

The amount of input substrate determines the number of digesters to be installed. Above the substrate level there is space for produced biogas. External gas storage is required to store gas during maintenance of gas utilisation equipment or low biogas demand period. For inoculation of the process, part of the digestate is recirculated and put back into the digester. A wall and floor heating system guarantees the required process temperature (mesophilic or thermophilic). Digestate is aerobically post treated (rotting process), hence a higher dry matter content is required, which is gained through solid liquid separation (separator). Liquid digestate is buffered in storage tanks.

EFFICIENCY:

In the field of solid waste treatment, continuous fermentation is the process with the highest process stability, lowest energy demand and lowest emissions. The balance between maximum gas production, minimum emissions and optimum digestate quality for an adjacent aerobic post treatment is guaranteed.

COSTS:

Compared to discontinuous treatment, the investment cost is higher, because substrate pre-treatment and digester technology is more sophisticated. The continuous operation and related automated loading and de-loading of the system leads to lower operational costs. Higher income can be generated because of increased gas production.

ADVANTAGES:

- Energy utilisation of municipal solid waste with simple pre-treatment
- Reducing emissions
- Reduction in landfill disposal in the case of treatment of previously landfilled waste

DISADVANTAGES:

- Initial investment for the plant is high
- Operation and maintenance are more extensive than for garage or pit digesters
- Requirement of constant substrate supply to justify investment and operation costs
- Regular technical service required for key equipment

3.1.5 Non-agitated covered lagoons

This type of digester is an adaptation of a simple manure lagoon where an installed impermeable cover traps the produced biogas (Figure 9). This system is not considered cost effective for the production of biogas in cold climates. However, it offers an effective reduction of odour emissions at a relatively low investment.

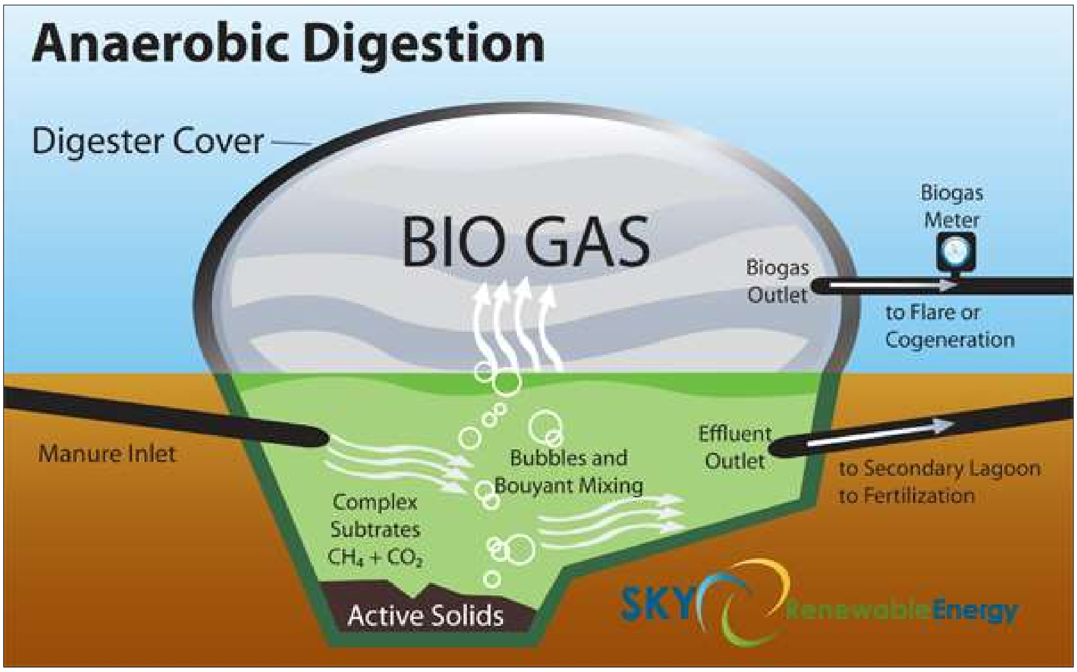

Figure 9: Scheme non-agitated covered lagoon (source: www.skyrenewableenergy.com)

PRE-TREATMENT OF SUBSTRATES:

Since this system is only able to treat manure or wastewaters with solid contents below 5% DM, a previous phase separation is required, after which only the liquid phase is sent into the lagoon. The solid fraction could be used for composting.

CONSTRUCTION AND EQUIPMENT:

The lagoon usually has the geometry of a reversed pyramid frustum. The slope of its walls depends on soil conditions. A geotextile and HDPE liner seal the lagoon against leakage.

COSTS:

Depends on plant size and components/material used. The investment cost for covered lagoons ranges from below €50/m^3 up to €300/m^3 lagoon volume.

In addition to the earthworks and installation of the geotextile and HDPE liner, the fixing of gas storages should be considered when determining the initial investment of a lagoon.

ADVANTAGES:

- Economic agricultural alternative
- Utilisation of waste
- Independence of commodities
- Intensifying possible livestock activity
- Increasing the quality of fertilisers

DISADVANTAGES:

- Low biogas production rate
- Settlement problems within digester results in frequent cleaning requirements, which temporarily halts biogas production
- Very liquid substrate only can be treated

3.1.6 Agitated covered lagoons

Agitated covered lagoons are an adaptation of complete mixed tank reactors. In contrast to CSTR plants using concrete or steel tanks, the digester of agitated covered lagoons is installed in open ponds (Figure 10). Insulating these lagoons against heat losses is not feasible. Hence, it only makes sense to implement these types of reactors in locations with a warm climate and a sufficient distance to a water table. Still an external heat exchanger is required to maintain the required process temperature. Multiple substrates, e.g. manure and other pumpable or pre-treated material (DM 10 to 15%) can be treated.

Figure 10: Agitated covered lagoon treating pig manure and abattoir waste (source: AD Solutions UG)

PRE-TREATMENT OF SUBSTRATES:

Basic CSTR system requirements are valid (Dry matter content of up to 10 %).

CONSTRUCTION AND EQUIPMENT:

The lagoon usually has the geometry of a reversed pyramid frustum. The slope of its walls depends on soil conditions. A geotextile and HDPE liner seal the lagoon against leakage.

A gas-tight cover serves as gas storage. Here, the same systems as for the CSTR are used. Depending on the dimensions, it can be useful to span one or more bridges over the lagoon, to reduce the size of the gas storage and implement several systems. These bridges can also serve as a fixing point for agitators.

Mixed covered lagoons are agitated by conventional mixing technology (agitators or circulation pump). Deeper lagoons have a better surface to height ratio, which results in an increased agitation of its content. An external heat exchanger or heating pipes installed within the lagoon (structurally more difficult to realise) guarantee a stable process temperature. Further equipment such as pumping stations, substrate pre-treatment, pipe installations, reception tanks, instrumentation and control systems correlate with those used at CSTR plants.

EFFICIENCY:

Depending on ambient temperatures, the necessary thermal capacity for heating and available thermal energy varies. If an optimal temperature condition can be maintained and under the consideration of an almost complete agitation of the lagoon's content a treatment efficiency comparable to a CSTR can be considered. Depending on input substrate gas production rates of approx. 0,7 to >3 m^3 Biogas/m^3 lagoon and day can be expected.

COSTS:

In addition to the earthworks and installation of the geotextile and HDPE liner, the ring foundation for fixing of gas storages should be considered when determining the production costs of a lagoon. Compared to a CSTR tank, investment costs are comparable except for the tank, which is replaced by the lagoon. This reduces both investment costs and construction time, as less equipment has to be imported.

Operational costs are expected to be in the same range as for CSTR technologies around 2% to 3% of the investment costs annually, plus the operational costs of the CHP as specified in chapter 3.2.2.

ADVANTAGES:

- Economic robust and flexible technology
- Processing of different types of organic waste mixtures
- Easy to install compared to conventional CSTR technologies
- Independence of commodities
- Intensifying possible livestock activity
- Transferring organic waste into fertiliser

<u>DISADVANTAGES:</u>

- Trained operating staff required
- Regular technical service required for key equipment
- Seasonality in agricultural production
- High space demand and competition for agricultural land and other use

3.1.7 Small scale household (rural) digesters

Worldwide more than 30 million small-scale household digesters are operated, most of them in rural Asia (Rajendran et al., 2012). Main substrates are animal dung and human excrement. Produced biogas is usually used to substitute combustibles (Figure 11).

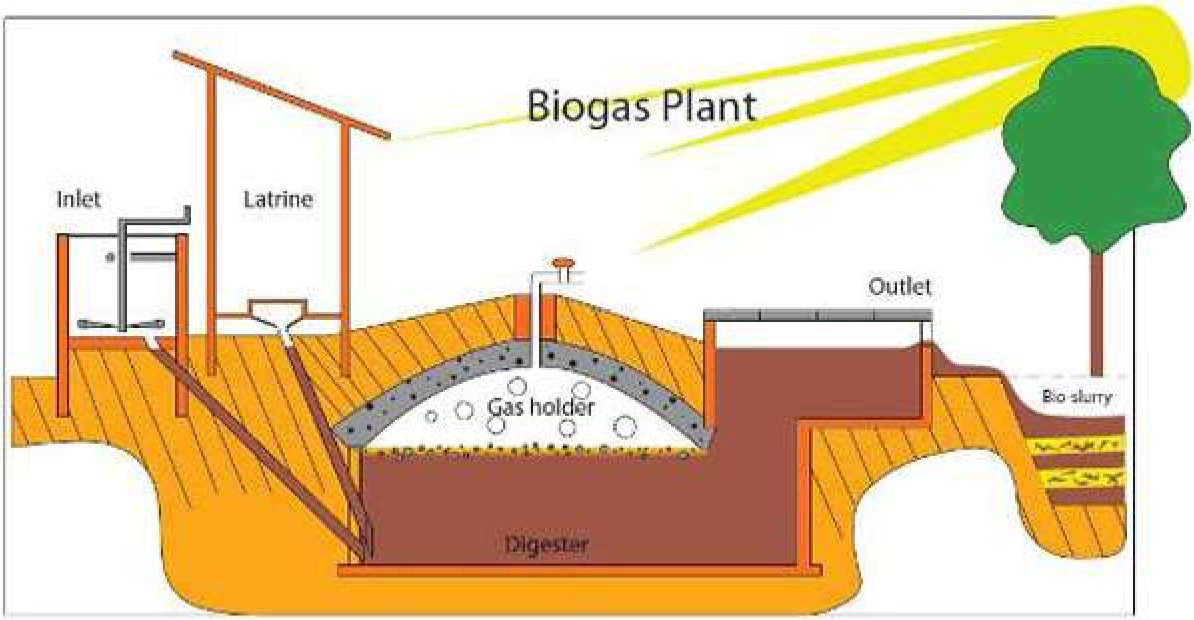

Figure 11: Household biogas digesters (source: www.naturalbuildingblog.com)

<u>Fixed-dome digester</u>

Fixed dome digesters consist of a closed tank with fixed gas storage (Figure 12). Produced biogas is stored in the upper part of the tank and replaces substrate into the outflow tank. The less gas present inside the gas storage, the lower the gas pressure.

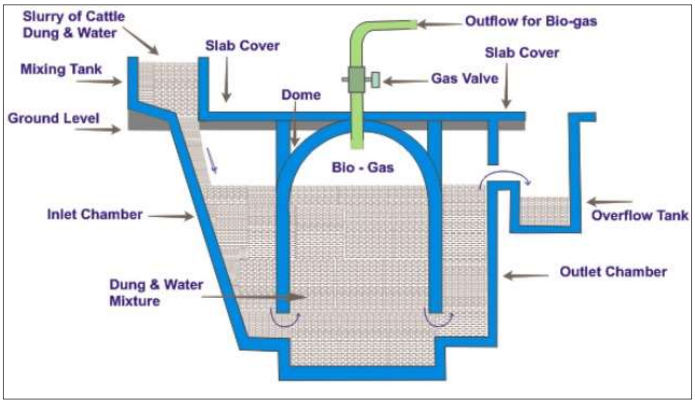

Figure 12: Fixed dome digester (source: http://bio-gas-plant.blogspot.de/p/biogas-plant-photos.html)

Floating drum digester

Floating drum dome digesters consist of a tank with moving gas storage (Figure 13). Produced biogas is collected inside the gas drum, which rises by the gas pressure. If gas is removed from the drum, it lowers again.

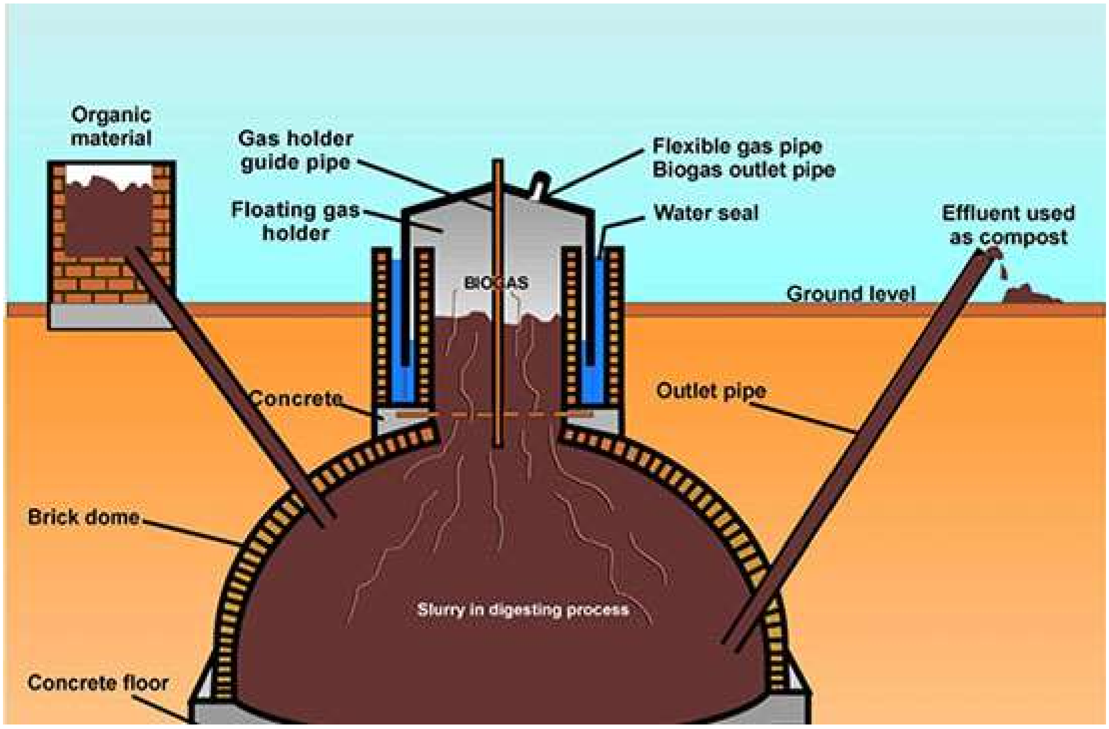

Figure 13: Floating drum digester (source: www.bioenergyconsult.com)

PRE-TREATMENT OF SUBSTRATES:

By mixing manure with water, the dry matter content shall be adjusted varying from 5% to 10% DM.

CONSTRUCTION AND EQUIPMENT:

The size of this type of digester ranges from 1 to 20 m^3. They can be made from bricks or polyethylene and a coating would be required, as they need to be gas-tight. If a floating drum is used, it is recommended that polyethylene is also used, since steel drums are not resistant to corrosive trace gases in biogas. Due to the fact that household digesters are usually fed by hand, no machinery (e.g. pumps or macerators) is required for the operation.

ADVANTAGES:

- Easy to implement
- Little equipment needs to be imported
- Improved disinfection of wastes/manure
- Production of valuable organic fertiliser
- Creation of jobs for biogas plant manufacturers

DISADVANTAGES:

- Poor gas yield due to lack of agitation and heating
- Settlement problems within digester results in frequent cleaning requirements, which temporarily halts biogas production
- Very liquid substrate only can be treated
- Only small digester volumes can be realized thus only small amounts of biogas can be produced

3.1.8 Comparison of biogas systems

The following table features a comparison of the different biogas systems using various critical factors for the projects in Tongatapu.[2]

[2] The table is a tentative evaluation only. The detailed technical evaluation based on the available input substrate is subject to report of deliverable III.

Table 1: Comparison of biogas systems

Technology	Dry matter content accepted	Technological Maturity	Operation in stormy regions (1: easy…. 5: impossible)	Installation in remote regions (1: easy…. 5: impossible)	Trained operating staff required (1: min…. 5: max)	Technical service required (1: min…. 5: max)
Continuous flow Stirred Tank Reactor (CSTR), basic version	<20%	> 10000 plants	4	3	3	4
Continuous flow Stirred Tank Reactor (CSTR), advanced version	<20%	>10000 plants worldwide (related to all kind of CSTR)	2	4	4	4
Garage or pit fermenters	35 to 45%	500 to 750 plants	2	3	4	4
Plug-flow digester or horizontal dry-fermentation digester	25 to 30%	500 to 750 plants	2	4	5	5
Non agitated covered lagoons	5% to 10%	More than 1000 worldwide	4	2	2	2
Agitated covered lagoons	<10%	<100 world wide	4	3	3	4
Small scale household digesters	Max 5%	Used worldwide	1	1	1	1

3.2 Technologies for biogas purification and biogas utilisation

Biogas could serve various purposes such as thermal energy production in fuelling boilers, furnaces, and kilns. It can generate electricity with CHP units for own consumption or feed-in the electricity grid. Biogas could be upgraded and used as alternative fuel for vehicles, or it can be upgraded to bio-methane and fed into an existing gas grid.

The objective of the Tonga Circular Economy Project is the production of electrical energy. Hence, only the production of electricity and heat/cool as by-product is evaluated in the following.

3.2.1 Overview on biogas purification

To utilise biogas to produce electrical and thermal energy (heat or cool), raw biogas needs to be cleaned from its major contaminants (mainly H_2S and humidity).

3.2.1.1 Biogas drying (removal of humidity)

The amount of water and water vapour that biogas can absorb is dependent on its temperature and should be removed to meet the requirements of the later stages of purification and protect the gas processing components against wear and corrosion. In the digester, the biogas relative humidity is 100% (fully saturated) and drying is performed by condensation (cooling), adsorption (silica gel, activated charcoal) and absorption (dehydration glycol). The method of cooling by removal is the most common method and is explained below.

CONDENSE DRYING:

This method of biogas drying is based on the principle of condensation by cooling the gas below its dew point. In cooler regions, this can be achieved by installing the gas pipes below ground, which cools down the biogas with the help of the soil temperature. It is mandatory that the gas pipes slope, to ensure that the condensed water can accumulate in the deepest point, where it is led into a condensate trap and eventually removed from the pipe system. Without a condensate trap, the gas pipe is likely to be clogged with condensate water. In regions with milder climates such as Tonga, it is necessary to actively cool the biogas below its dew point. This is usually done by using a heat exchanger, where a condensate trap remains a necessary piece of equipment.

3.2.1.2 Desulphurisation (removal of H_2S)

The removal of sulphur is necessary to protect plant equipment from corrosion. There are several methods of desulphurisation, which can be categorised as biological, chemical and physical (Table 2).

Table 2: Overview of desulphurisation methods

Method	Energy demand el.	Consumables		Air injection	Purity in ppm	Problems
		Consumption	Disposal			
Biological desulphurisation inside digester	++	++	++	Yes	50-2000	Imprecise process control
External biological desulphurisation	-	+	+	Yes	50-100	Imprecise process control
Bioscrubber	-	-	+	No	50-100	High process cost and complexity
Sulphide precipitation	O	--	o	No	50-500	Sluggish process
Internal chemical desulphurisation	O	--	--	Yes	1-100	Greatly diminishing purification effect
Activated carbon	o	--	-	Yes	<5	Large disposal volumes
++ particularly advantageous, + advantageous, o neutral, - disadvantageous, - - particularly disadvantageous.						
Source: Guide to biogas, 2012.						

<u>Injection of air into the digester</u>:

An affordable and effective method to reduce the sulphur content in biogas is to inject air into the reactor’s gas phase (Figure 14). The same types of bacteria in the trickle bed reactor are used for this application. No external reactor is used, but the process takes place in the digester itself.

Figure 14: Layer of sulphate produced by desulphurising bacteria inside a digester (source: www.biogaskontor.de)

<u>TRICKLE BED REACTOR</u>:

One of the typical desulphurisation units used in biogas plants is the trickle bed reactor (Figure 15). This is a continuously working application that uses special micro-organisms which oxidise sulphur into sulphate in an external reactor by using air, which is injected into the reactor.

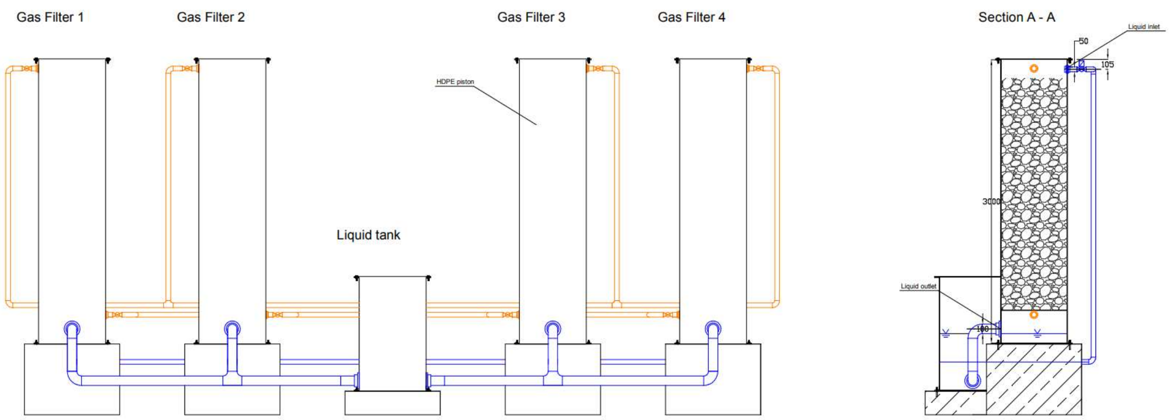

Figure 15: Scheme trickle bed reactor (source: AD Solutions UG)

SIMULTANEOUS DOSING OF IRON:

This application works by dosing iron compounds, such as iron salts or iron hydroxide (Figure 16), together with fresh substrate into the digester. The iron components react with the sulphur present inside the substrate and form insoluble sulphide, which can, together with digestate, be removed from the digester.

Figure 16: Picture of iron hydroxide powder (source: www.nectaec.de)

IRON OXIDE:

By using an external reactor filled with iron oxide and sending the raw biogas through it, effective desulphurisation can be achieved. The iron oxide needs to be replaced frequently, once it is saturated.

ACTIVATED CARBON ADSORPTION:

By sending the raw biogas through an external reactor filled with activated carbon (Figure 17), excellent results can be achieved. Once the carbon is saturated, it needs to be replaced with new material, which makes this application relatively costly.

Figure 17: Activated carbon filter (source: www.gutmbh.de)

3.2.1.3 Elimination of siloxanes

Biogas originating from organic wastes, municipal or industrial wastewaters can contain increased concentrations of siloxanes. When combusted in gas engines, these form abrasive sediments inside the engine and lead to increased use of mechanical components.

Biogas plants solely treating substrates originating from agricultural sources usually do not have problems with increased siloxanes concentrations. But if de-foaming agents or other chemical additives are used, siloxanes can become a problem.

Hence siloxanes need to be removed from the raw biogas.

<u>ACTIVATED CARBON ADSORPTION</u>:

By sending raw biogas through an external reactor filled with a siloxanes adsorbing activated carbon, the biogas can be cleaned to an extent, which eliminates potential damages to subsequent equipment.

The holding time of the activated carbon filter needs to be designed according to the biogas' siloxane load. Continuous analyses of the cleaned gas should be performed to guarantee timely replacement of saturated activated carbon.

3.2.2 Utilisation of biogas

As previously mentioned, the objective of the study is the production of electrical energy by utilizing the produced biogas in a stationary CHP (Figure 18).

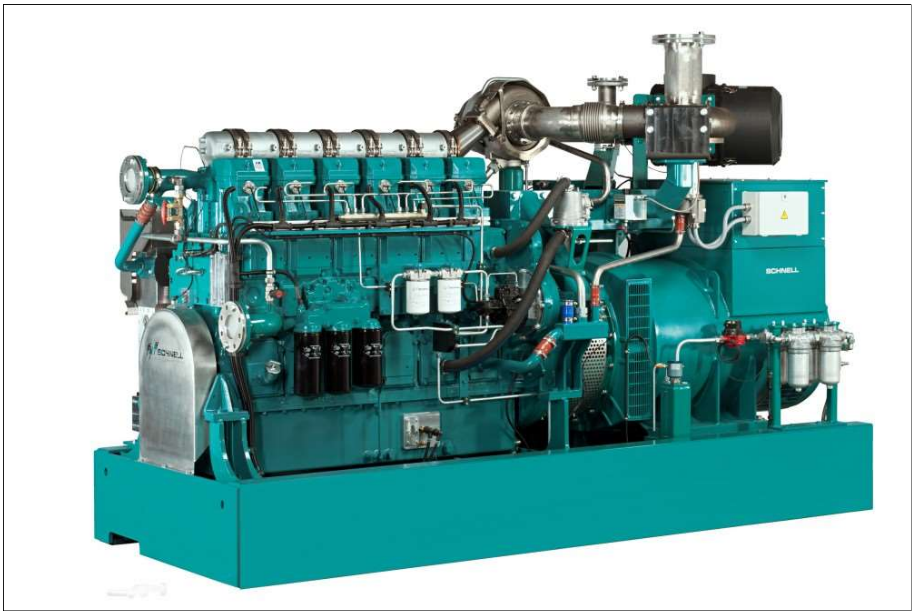

Figure 18: CHP unit Company Schnell (source: www.whg-anlagenbau.de)

DESCRIPTION OF THE PROCESS:

CHP units simultaneously generate heat and electricity with a combustion engine connected to an electricity generator.

Modern CHP units can have a total efficiency of up to 90% of the energy contained in the gas. Heat is extracted in four places:

- Cooling water from the engine block
- In the cooled exhaust manifold with water
- In the gas heat exchanger
- In the intercooler (intermediate cooling)

Produced heat can usually be used at a temperature of around 80°C, with a temperature difference of 20K between input and output.

GAS SPARK IGNITION ENGINES:

These engines have been developed exclusively for burning a gaseous fuel, and based on the principle of Otto engines, utilise the excess air to reduce CO_2 and SOx emissions. To incinerate biogas, a minimum methane concentration of 45% is required. The life expectancy of gas spark ignition engines range from 40,000 to 60,000 hours operation time. The typical performance is between 50kW$_{el}$ and 2MW$_{el}$.

DUAL-FUEL ENGINES:

These engines originate from truck engines and work on the principle of diesel engines. To operate they require a mixture of diesel (or another fuel oil) and biogas. These engines also operate with excess air and require a fuel oil injection (corresponding to 2% to 10% of the supplied fuel power) in the combustion chamber to aid combustion and cooling the injection nozzle (carbonisation). For this process, there are two concepts of control that must be taken into consideration:

- Operation controlled by the amount of biogas - load control is effected by means of the gas system, i.e. the motor operates at constant volume of diesel and variable gas volume.
- Constant power regulation - in the absence of gas, diesel fuel acts as compensation.

Dual-fuel engines usually come with an installed capacity of up to 500kW$_{el}$, with less operational time than that of gas engines. It is possible to operate solely on diesel dual-fuel engines, for example, as an emergency generator. The power in this case is limited to 60% of the nominal power.

GENERATORS:

Either synchronous or asynchronous (induction) generators are used in combined heat and power units. Because of high reactive current consumption, it makes sense to use asynchronous generators only in units with a rating lower than 100 kW$_{el}$. Consequently, synchronous generators are normally used in biogas plants.

INPUT:

The use of biogas in gas engines requires a minimum methane content of 45% and a H_2S content below 400ppm. It should also be free from water vapour and siloxanes.

EFFICIENCY/PRODUCTIVITY:

The electrical efficiency of CHP units range from 30% to 45%. Thermal efficiency ranges between 50% and 60%. This leads to total efficiencies of up to 90%.

COSTS:

As shown in Table 3, the specific cost significantly depends on the installed capacity. Operational costs usually range around €0,015/kWh of electricity produced.

Table 3: Specific investment costs for gas engines

Type	Potential	Investment cost
Gas spark ignition engines	100 kW	1.200 EUR/kW
	600 kW	600 EUR/kW
Dual-fuel engines	50 kW	1.400 EUR/kW
	100 kW	800 EUR/kW
	250 kW	450 EUR/kW
Source: Adaption FNR, 2013.		

TECHNOLOGICAL MATURITY/ INTERNATIONAL COUNT:

Both types of engines are state-of-the-art and are widely spread all over the globe.

ADVANTAGES AND DISADVANTAGES:

Table 4: Comparison of different gas engines

Gas spark ignition engines	
Advantages	**Disadvantages**
• Designed specifically for gas • Lower emissions • Lower maintenance/ operational costs	• Higher investment costs • Lower efficiency in lower power range
Dual-fuel engines	
Advantages	**Disadvantages**
• Lower investment costs • High efficiency in lower power range • Simple operation • No complex gas treatment required	• Higher maintenance costs • Additional use of fuel oil • Emissions
Source: Adaption FNR, 2013.	

4 Biogas technology recommended for application in Tonga

4.1 Biogas system recommended

Evaluation of literature data of potential biogas substrates available in Tonga has shown that a diverse mixture of small amounts of different kind of manure and organic waste might be available. Since the plant should continuously produce at least 500 kW of electricity on average, the biogas technology installed should be able to treat different kind of manure as well as renewable energy crops, as e.g. Hydro Tropical Grass, to increase the biogas potential significantly.

For this reason, the biogas technology to be installed needs to be able to handle different kinds of substrate and thus various substrate compositions (liquid, sludgy, solid).

This requirement already eliminates three (Agitated covered lagoons, Non agitated covered lagoons, Small scale household digesters) of the seven technologies listed in

Table 1, since these technologies are not able to treat substrate mixtures with high solid content.

Since Tonga is a very remote island with limited biogas technology spare part supply chain, a robust technology that is as easy to install, operate and maintain should be preferred. Therefore, it is not recommended to install sophisticated technologies such as CSTR-advanced version or dry-fermentation digester.

Garage or pit fermenter are developed for very solid substrate mixtures and accept high rate of impurities but provide comparatively low efficiency.

Since the expected substrate composition does not indicate the presence of large impurities and efficiency is an important issue, the CSTR-basic version seems to be the most appropriate biogas technology for Tonga.

Usually, this kind of digester is covered with a double membrane gas storage. Due to the storms (cyclones), which are to be expected in Tonga, an alternative digester cover (concrete or steel) should be implemented. The produced biogas should be stored in an external gas storage, which can be more easily secured against a storm. In addition, external gas storages can be designed to be relatively large which allows greater quantities of gas to be stored temporarily. If generator (CHP) capacities were increased at the same time, biogas electricity could balance intermittent renewable energy sources such as solar and wind and could be used for load management and supply of peaks.

4.2 Biogas purification and biogas utilisation recommended

Regarding the gas desulphurisation, the focus should be on technologies with the lowest possible need for additives that have to be imported. Therefore, the most efficient biological desulphurisation inside the digester should be installed for maximum H_2S reduction through this technology. To eliminate the remaining H2S it is recommended to apply substances which can remain on the island such as iron salts or iron hydroxide as the iron would remain in the digestate and thus form part of the fertilizer to be applied.

Since the CHP unit is the most maintenance-intensive device in the biogas plant and due to the limited access to technical service in Tonga, it is very essential to choose a simple and robust CHP technology. As pointed out in Table 4, dual-fuel engines have higher maintenance costs, but lower investment costs and most importantly these engines are easier to operate and do not require complex gas treatment systems. Furthermore dual-fuel engines are modified diesel engines which means that technicians who are able to fix a diesel engine are probably also able to perform basic maintenance for dual-fuel engines.

5 Glossary (directly quoted from: Glossary of (FNR) (2012))

Ammonia (NH_3): Nitrogenous gas arising from the degradation of nitrogen-containing compounds such as protein, urea and uric acid.

Anaerobic degradability [1]: Degree of microbial conversion of substrates or co-substrates, generally expressed as biogas generation potential.

Anaerobic micro-organisms [3]: Microscopic organisms that grow in the absence of oxygen. For some, the presence of oxygen can be lethal.

Anaerobic treatment [1]: Biotechnological process taking place in the absence of air (atmospheric oxygen) with the aim of degrading organic matter to recover biogas.

Biogas [1]: Gaseous product of digestion, comprising primarily methane and carbon dioxide, but which, depending on substrate, may also contain ammonia, hydrogen sulphide, water vapour and other gaseous or vaporisable constituents.

Biogas plant [4]: Plant designed for the production, storage and utilisation of biogas, including all equipment and structures required for operation of the plant. Gas is produced from the digestion of organic matter.

Carbon dioxide (CO_2) [5]: Colourless, non-combustible, mildly sour-smelling, intrinsically non-toxic gas formed along with water as the end product of all combustion processes; concentrations of 4 to 5% in air have a numbing effect, while concentrations of 8% or over can cause death from asphyxiation.

Co-substrate [1]: Raw material for digestion, albeit not the raw material accounting for the largest percentage of the material stream to be digested.

Combined heat and power (CHP) unit: Unit for the conversion of chemically bound energy into electrical and thermal energy on the basis of an internal combustion engine coupled to a generator.

Combined heat and power (cogeneration): Simultaneous conversion of input energy into electrical (or mechanical) energy and heat for energy-related use (useful heat).

Condensate: Biogas produced in the digester is saturated with water vapour and must be dehydrated before being used in a CHP unit. Condensation takes place either via an appropriate underground pipe into a condensate separator or by drying of the biogas.

Degree of degradation [1]: Extent to which the initial concentration of organic matter in the substrate is reduced as a result of anaerobic degradation.

Desulphurisation: Physio-chemical, biological or combined method of reducing the hydrogen sulphide content in biogas.

Digestate: Liquid or solid residue from biogas production containing organic and inorganic constituents.

Digestate storage tank (liquid manure pond) [4]: Tank or pond in which liquid manure, slurry or digested substrate is stored prior to subsequent use.

Digester (reactor, digestion tank) [4]: Container in which a substrate is microbiologically degraded and biogas is generated.

Dry matter (DM) content: Moisture-free content of a mixture of substances after drying at 105 °C. Also referred to as total solids (TS) content.

Emissions: Gaseous, liquid or solid substances entering the atmosphere from a plant or technical process; also includes noise, vibration, light, heat and radiation.

Energy crops [5]: Collective term for biomass utilised for energy-related purposes (not fodder or food). As a rule these are agricultural raw materials such as maize, beet, grass, sorghum or green rye that are ensiled before being put to use for energy-related purposes.

Full-load hours: Period of full utilisation of a plant's capacity; the total hours of use and average utilisation factor over a year are converted to a utilisation factor of 100%.

Gas dome [4]: Cover on a digester in which biogas is collected and drawn off.

Gas storage tank [4]: Gas-tight vessel or plastic sheeting sack in which biogas is held in temporary storage.

Hydrogen sulphide (H2S) [4]: Highly toxic, colourless gas with a smell of rotten eggs; can be life-threatening even in low concentrations. From a certain concentration the sense of smell is deadened and the gas is no longer perceived.

Methane (CH4) [8]: Colourless, odourless and non-toxic gas; its combustion products are carbon dioxide and water. Methane is one of the most significant greenhouse gases and is the principal constituent of biogas, sewage treatment gas, landfill gas and natural gas. At concentrations of 4.4 vol. % or over in air it forms an explosive gas mixture.

Nitrogen oxide [8]: The gases nitrogen monoxide (NO) and nitrogen dioxide (NO2) are referred to collectively as NOx (nitrogen oxides). They are formed in all combustion processes as a compound of atmospheric nitrogen and oxygen, but also as a result of oxidation of nitrogenous compounds contained in the fuel.

Organic loading rate [1]: Amount of substrate fed into a digestion plant per day in relation to the volume of the digester (unit: kg VS/(m^3 ·d))

Potentially explosive atmosphere [4]: Area in which an explosive atmosphere may occur due to local and operational conditions.

Preparation: Process step for the treatment of substrates or digestates (e.g. comminution, removal of interfering substances, homogenisation, solid/liquid separation).

Retention time [1]: Average holding time of the substrate in the digester. Also referred to as dwell time.

Silage: Plant material conserved by lactic acid fermentation.

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Siloxanes: Organic silicon compounds, i.e. compounds of the elements silicon (Si), oxygen (O), carbon (C) and hydrogen (H).

Solids infeed: Method of loading non-pumpable substrates or substrate mixtures directly into the digester.

Substrate [1]: Raw material for digestion or fermentation.

Throughput: Depending on definition, this is either a volumetric flow rate or a mass flow rate.

Volatile solids (VS) content: The volatile solids content of a substance is what remains after the water content and inorganic matter have been removed. It is generally determined by drying at 105 °C and subsequent ashing at 550 °C.

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