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Characterisation of biogas storages: influences and comparison of methods

Mathias Stur, Marcel Pohl, Christian Krebs, Eric Mauky

Storage of the gas produced by biogas plants is an integral part of the operating concept, regardless of the further utilisation. Especially as biogas nowadays has become a means of on-demand power production, storage no longer only serves to compensate for fluctuations due to weather conditions or in the event of operational disruptions, but has become an important component for participation in the electricity market.

This article provides an overview of the various gas storage systems and their filling level measurement systems applicable in practice. Furthermore, based on research at the DBFZ, it shows various methods for determining the usable volume of gas storage systems on biogas plants. The different methods are classified, compared and discussed according to the reliability of the results. Additionally, influences of weather conditions on the usable storage volume are described.

Keywords
Biogas storage, filling level measurement, net gas storage capacity, weather influence, volume determination

For the storage of gases, systems adapted for different applications are used. The following classification of storage systems is limited to the storage of biogenic methane-containing gases, which are produced during anaerobic digestion. The biogas produced usually consists of 50 to 60% methane, with the remainder being mainly carbon dioxide. Furthermore, portions of hydrogen sulfide and hydrogen, siloxanes and ammonia can be contained in small amounts. As the feed-in of upgraded biogas to biomethane into the natural gas grid is gaining importance, natural gas storage systems are also included in the classification.

State of the art

Gas storage systems can firstly be classified according to their operating principle. Here, they are divided into wet and dry gas storage. In a wet gas storage, a sealing liquid is used to seal the gas compartment from the environment. This principle is very simple, low in wear and has a high degree of tightness. The bell gas storage is an example, in which the bell is floating in a water-filled ring. The operating pressure is technically very low because the pressure in the gas compartment is limited by the displaceable water column in the ring. The gas is compressed slightly during filling and the associated lift of the bell. Therefore, wet gas storages have a high space requirement depending on the storage capacity. During operation, the sealing points must be protected against freezing (Braun 1982). In contrast, dry gas storages are designed with various forms of sealing, such as threaded fittings, plastic or metal surface seals or greased, friction piston ring seals. This allows a higher internal gas storage pressure and therefore results in lower space requirements. The next subdivision is made

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according to the applicable pressure into a low, medium and a high-pressure stage. The ranges of the relative overpressure to the atmosphere are defined as follows:

- Low pressure stage $1 < p < 100$ hPa

For better comprehensibility, the usual range of the low-pressure stage has been extended to $1 < p < 100$ hPa. The term unpressurised is avoided and this pressure range is assigned to the low-pressure stage, as the applied relative overpressures are in the range of 1 to 10 hPa.

- Medium pressure stage $100 < p < 1.000$ hPa
- High pressure stage $p > 1.000$ hPa

The wet gas storages are operated in the low-pressure stage due to their mode of operation. In the case of dry gas storages, the use varies depending on the design from ambient pressure to high-pressure applications with compressed gas cylinders with up to 30 MPa. A further classification is made with regard to the design of the gas compartment. There are storage systems that can be space-variable. These are not isobaric systems. By adding a quantity of gas, the gas compartment is enlarged. This happens by expending a flexible and partly mass-loaded, expandable or non-expandable membrane or by displacement of an apparatus, e.g. similar to a lifting piston. For instance, the gas pressure-supported single-shell membrane gas storage is equipped with an expandable membrane and forms itself into a spherical calotte shape with increasing gas volume, supported by the resulting increasing internal gas storage pressure. The pretensioning of the membrane results in a defined shape of the membrane (Figure 1.4). The mechanically preloaded double-shell membrane gas storage is designed with two flexible, non-expandable membranes. Figure 1.5 shows the structure of the gas storage system with a yellow gas storage inner membrane, which is attached gas-tight to the support column, and an outer mechanically preloaded grey outer membrane. The inner membrane is shaped depending on the gas volume until it comes into contact with the outer membrane. The internal gas storage pressure increases as the filling level increases.

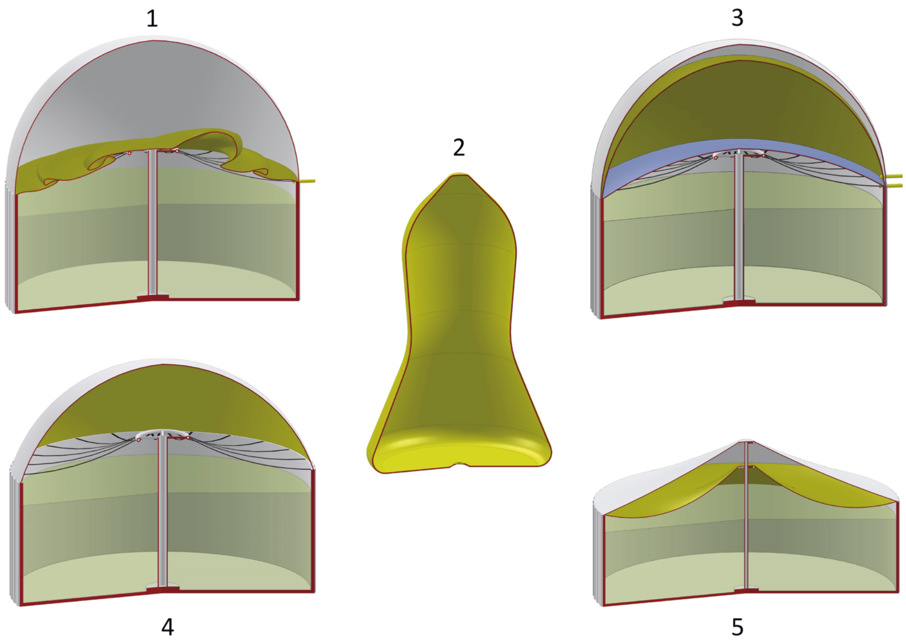

Figure 1: Selected designs of gas storage systems; 1 - integrated pneumatically preloaded double-shell membrane gas storage (partially filled); 2 - membrane gas bag suspended (partially filled, without supporting structure and enclosure); 3 - integrated pneumatically preloaded three-shell membrane gas bag (fully filled); 4 - gas pressure-supported single-shell membrane gas bag (fully filled); 5 - mechanically preloaded double-shell membrane gas bag (deflated)

Furthermore, isochoric, space-invariant systems are used that allow for the gas to be compressed, as in the use of a compressed gas cylinder.

Finally, gas storage systems are classified according to the type of integration of the gas storages within the structural system. A distinction is made between integrated and separated systems. Integrated systems are storage types that are directly connected to the biogas-producing fermentation tank as a roof design. Separated systems are externally located and stand-alone gas storage systems. An example of the separated gas storage design is the suspended membrane gas bag (Figure 1.2).

Depending on the design, the storage systems are referred to as single-shell, double-shell or three-shell storages. Designs with one membrane between the gas compartment and the environment are referred to as single-shell, the design with two or three membranes as double- or three-shell. A list of the individual gas storage systems and their classification is shown in Figure 2.

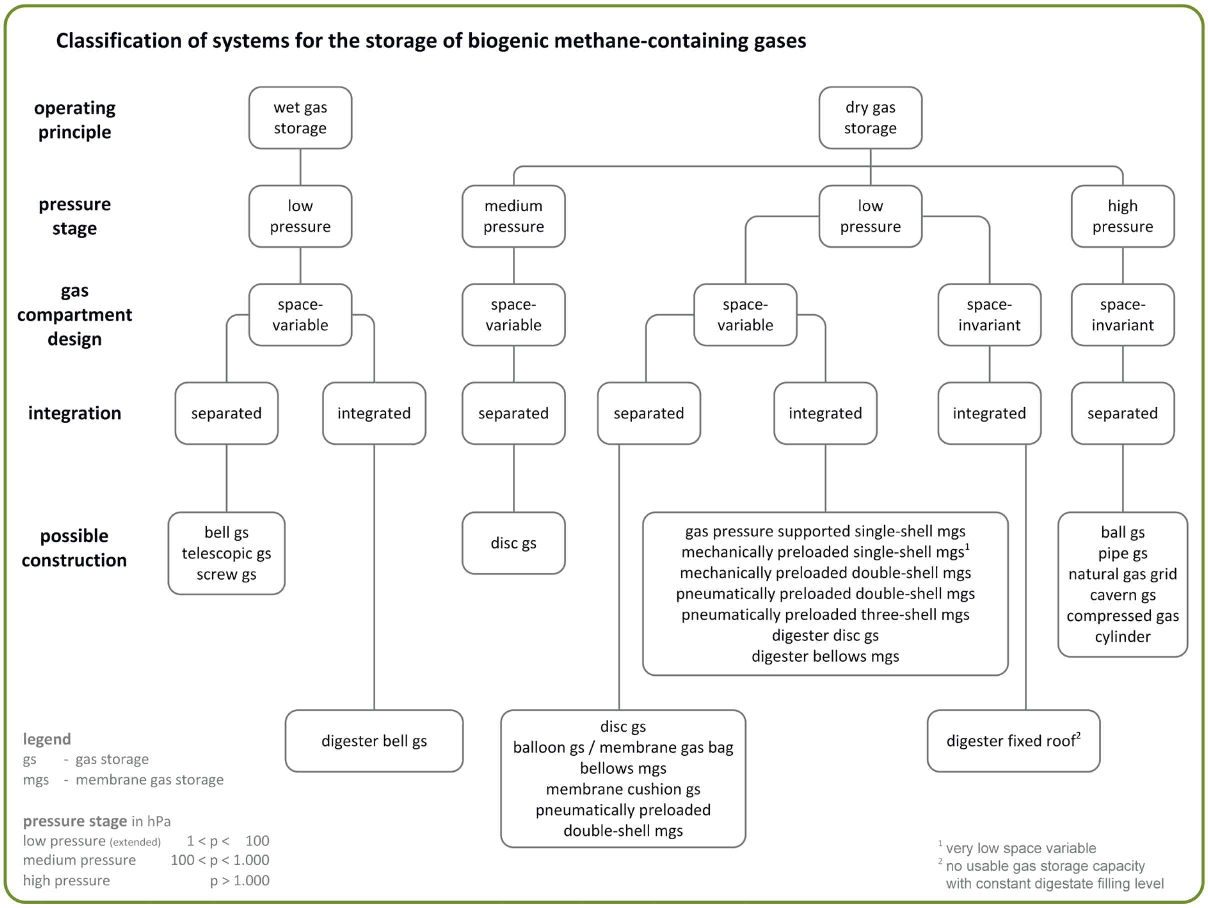

Figure 2: Classification of gas storage systems

The integrated double membrane gas storages are installed on fermentation tanks at around 63% of German biogas plants (Daniel-Gromke 2017). They are the most prevalent system in Germany for the temporary storage of biogas, which is why this type of construction and its technical design will be examined in more detail below.

Design and function of the double membrane gas storage

Structure

The integrated pneumatically preloaded double-shell membrane gas storage (double membrane gas storage) shown in Figure 3 is constructed from an outer membrane (Figure 3.1) and a gas storage inner membrane (Figure 3.2). Both membranes are designed to be flexible and non-expandable, attached to the upper edge of the tank wall (Figure 3.7) and, arranged above the fermentation tank, form the integrated gas-tight and space-variable storage roof. Through a specific configuration of the membrane construction, e.g. by a composite of several membrane layers, coatings and different materials, different properties, such as formability and tensile strength, UV resistance and permeation are achieved. The flexible tube (Figure 3.5) of the gas storage filling level measuring system is attached to the gas storage inner membrane. Under the gas storage inner membrane is the belt support system, consisting of the support column (Figure 3.9) and belts (Figure 3.3) extending radially to the outer wall of the tank. A net lays over the belts to support the gas storage inner membrane on the belt support system.

Outside the roof, a support air system (Figure 3.6) is integrated, consisting of a support air blower, e.g. a side channel compressor, a sectional flexible gas line from the blower to the outer membrane (support air feed point) with a passage into the support air compartment (Figure 3.13) and a partial flow switched damper flap. Opposite to the support air supply point is the support air feed-out point with a second gas line (Figure 3.13) and a damper flap. The pressure relief valve (Figure 3.4) and the biogas line (Figure 3.11) are each connected to the interior of the gas storage via an opening. The fermentation tank is equipped with a paddle agitator (Figure 3.8) and a side agitator (Figure 3.12) below the fermentation medium level (Figure 3.10).

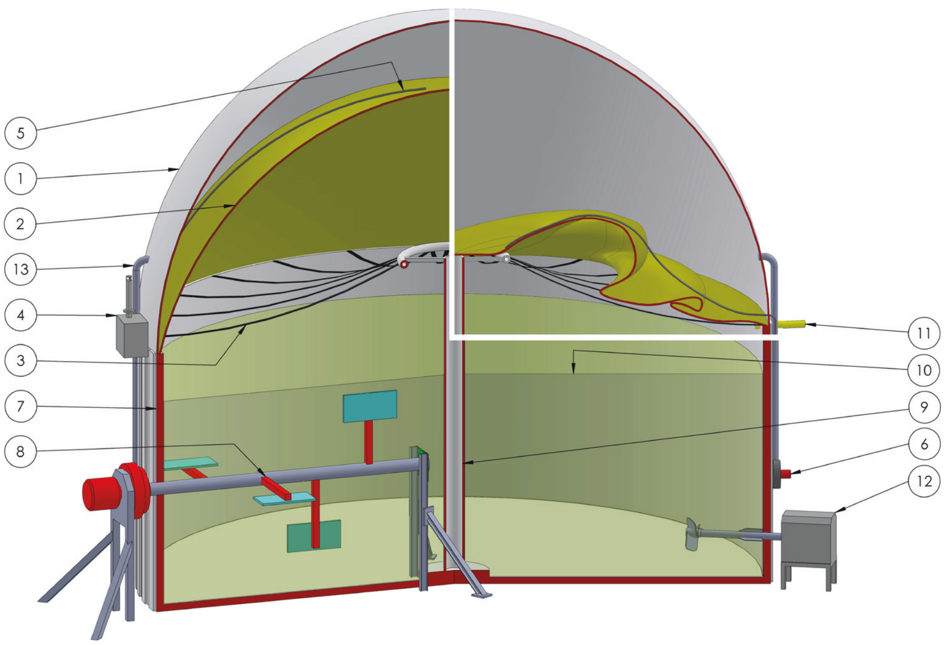

Figure 3: Assembly of a digester with integrated pneumatically preloaded double-shell membrane gas storage - (filled); section of white frame top right - partially filled, undefined shaping of the gas storage inner membrane; 1 - outer membrane, 2 - gas storage inner membrane, 3 - belt support system, 4 - pressure relief valve, 5 - hydrostatic pressure measuring system (gas storage filling level measurement system), 6 - support air blower with damper flap, 7 - insulated sheet steel tank shell, 8 - paddle agitator, 9 - support column, 10 - fermentation medium level, 11 - raw biogas feed-out, 12 - side agitator, 13 - support air feed-out with damper flap

Operating principle

At the beginning, the gas storage is in a technically empty state with the folded gas storage inner membrane resting on the belt support system and a correspondingly small amount of biogas in the gas storage. Due to the production of biogas in the fermentation tank, the gas storage fills up and the gas storage inner membrane is lifted out and carried depending on the amount of produced gas.

The support air blower feeds ambient air, into the support air compartment (Figure 4.5). This leads to an overpressure to the environment in the support air and gas storage interior and, as a result, to a permanent shaping of the outer membrane in the form of a spherical calotte. As the amount of biogas increases, the support air compartment becomes smaller and the net gas storage compartment between the belt support system and the gas storage inner membrane becomes larger (Figure 4.1). There is a balance of forces between the two gas compartments. The pressure generated by the support air volume flow is transferred to the gas storage compartment as a surface load via the gas storage inner membrane and the space-limiting fermentation tank. During the filling of the gas storage, the gas storage inner membrane, as shown in Figure 3 (upper right section), forms in an undefined manner. Factors such as

- the arrangement of inlet and outlet points for the support air and biogas,
- the installation position in the main wind and compass direction,
- structures installed on the inner membrane of the gas storage, such as measuring components, guide or hold-down systems to stabilise the shape of the membrane,
- as well as the construction and design of the membrane itself

can have an effect on the membrane shaping.

After the gas storage has reached a technically full state, the gas storage inner membrane follows the spherical calotte-shaped form of the outer membrane and, depending on the membrane design. In the upper pole cap area, a clearance between the outer membrane and the gas storage inner membrane must be ensured to allow for the support air to be distributed over the entire support air compartment, especially when the smallest support air compartment is reached, as shown in Figure 3.

Overpressure and underpressure events

When the gas storage inner membrane is placed on the belt support system, i.e., gas storage is empty, the balance of forces in the gas compartment is reduced and the gas storage inner membrane acts as an undesired pressure limitation between an overpressure in the support air compartment and a lower pressure in the gas storage during continuous biogas extraction (negative pressure event). Therefore, the overpressure in the support air compartment is transferred as a surface load to the gas storage inner membrane, resting on the belt support system, and is absorbed via the outer membrane, the support column with base foundation and the container wall. With the exception of the outer membrane, the negative pressure in the gas storage affects the same system parts and represents an operating condition to be avoided with a higher load on the system parts.

When the gas storage is transferred to the technically full state, the gas storage inner membrane is completely formed into a spherical calotte. If additional biogas is added to the isochoric gas storage that has been created or if there is a temperature-related gas expansion in the isochoric gas storage, the pressure rises from this moment onwards and an overpressure event occurs.

To prevent damage to the biogas plant due to excessive pressure loads, a safety device, the pressure relief valve, is used for both pressure events. This is triggered at a relative overpressure of approx. 5 hPa or a relative underpressure of < 0 hPa and blows biogas out of the gas storage in the event of overpressure or draws ambient air into the gas storage in the event of underpressure. When air is drawn into the gas storage, depending on the amount of air and the resulting gas concentration, the lower explosion limit (LEL) may be reached and an explosive atmosphere may be created. These aspects emphasise the necessity of an adapted internal gas storage pressure.

Support air system

The support air system is a system open to the atmosphere due to planned leaks such as membrane passages for e.g. measurement technology or damper flaps on the inlet or outlet side to the support air compartment. On the other hand, there are unplanned leaks such as leaks due to damage or wrong installation of the outer membrane. Through the position of the often mass- or spring-loaded damper flaps, the outgoing support air volume flow and thus the internal gas storage pressure can be set to an operating point. Short-term pressure fluctuations caused, e.g., by weather influences such as wind loads on the outer membrane can thus be compensated for by the movable damper flap.

Gas storage volumes

The double membrane gas storage is divided into two different gas-holding sections due to its integrated design directly on the fermentation tank. On the one hand, there is the gross gas storage volume, which holds the entire gas volume in the storage tank. On the other hand, there is the net gas storage volume, that is the variable volume of the inner membrane. Figure 4 shows the ranges of the two volumes described.

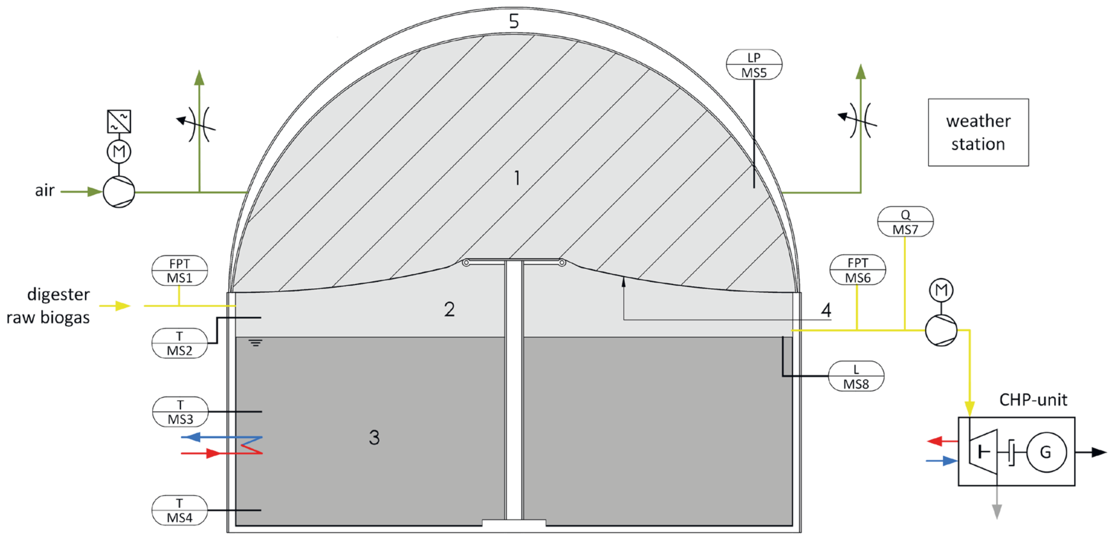

Figure 4: Representation of different gas storage areas in the technically full state; 1 - variable net gas storage volume (light grey hatched); 2 - variable gross gas storage volume (light grey and light grey hatched); 3 - fermentation medium volume (dark grey); 4 - belt support system; 5 - variable support air volume (white); legend measurement technique - F volume flow, L filling level, MS measuring point, P pressure, Q gas concentration and T temperature; weather station (Table2)

The net gas storage capacity represents the amount of biogas that can be stored and used. Depending on temperature and pressure, the available net gas storage capacity changes while the net gas storage volume remains constant. According to the ideal gas law, the same amount of gas requires more volume at a given pressure but higher temperature. Thus, as the internal gas storage temperature increases, the density of the heated and expanded gas decreases. Consequently, the net gas storage capacity decreases because less biogas volume can be stored.

The response behaviour of this gas storage is to be described with regard to pressure and temperature as well as the time-dependent deformation of the gas storage inner membrane and the resulting gas storage filling level. Essential findings on the shaping behaviour were presented above. Starting from a technically empty state, the gas storage pressure curve results in a constant pressure range over the entire gas storage filling level until the technically full state is reached. Slow pressure changes due to e.g. solar radiation, an increase in the ambient temperature or changes in the atmospheric pressure therefore do not lead to a short-term increase in pressure, as the shape of the gas storage inner membrane compensates for the expansion of the gas. Significant wind loads, on the other hand, can cause short-term pressure peaks in the pressure curve if the damper flaps, the support air volume flow set by them and the shape of the gas storage inner membrane do not ensure compensation. Due to the influence on the internal gas storage pressure by adjusting the support air volume flow, several corresponding gas storages can be adjusted to each other in such a way that a sufficient pressure difference between the gas storages and the conversion units can be realised for an optimal utilisation of the net gas storage capacity (Kube 2018). Depending on the system dimensions, long or angled pipes or unsuitable internal pipe diameters can lead to excessive pressure loss between the gas storages. In this case, a forced convection flow of the raw biogas must be set up using blowers or compressors to ensure the required gas flow.

Filling level measurement system

In practical applications for measuring biogas storage filling levels of different gas storage designs, the following three systems are mainly used.

- hydrostatic pressure measurement system
- rope-pull measurement system
- Internal gas storage pressure measurement system

The ultrasound measurement system for direct detection of the membrane shape of a gas storage cover is a comparatively rarely used variant. For completeness, the radar measurement system is mentioned, which can be used analogously to ultrasound measurement for monitoring the position of surfaces, liquid levels or membranes. In the following, the three most relevant systems are discussed in more detail.

Hydrostatic pressure measurement system

This system consists of a flexible tube filled with a water-glycol mixture, closed on one side and equipped with a transducer on the other side of the flexible tube. The transducer is attached to the outside of the tank wall and represents the lowest point of the measuring system structure. The tube is routed tangentially starting from the vessel wall bushing onto the gas storage inner membrane and routed to the pole cap. In the area of the pole cap, the end of the tube is fixed with eyelets. Due to the lift of the membrane as the gas storage volume increases, a change in hydrostatic pressure occurs in the tube, which is recorded by the transducer. By converting the water column pressure, the highest point of the tube can be determined and thus the filling level of the gas storage can be concluded.

Rope-pull measurement system

The rope pull system is a simple mechanical system that is mainly used for single, double and triple-shell membrane gas storages as well as for lying gas bags. The measurement setup comprises a rope and usually a counter mass. The rope is attached to the upper edge of the vessel wall and guided via a few eyelets along the upper side of the gas storage inner membrane and the pole cap onto the diametrically positioned outer membrane aperture, so that a relative movement of the rope to the membrane surface in rope alignment is ensured. A vertical guide tube is arranged on the opposite side after the breakthrough. A counter mass attached to the free end of the rope is guided concentrically in the guide tube. The counter mass is monitored in the vertical position and provides the necessary tensile pre-tensioning of the rope to prevent jamming and to ensure a tight fit against the membrane surface. The rope adapts to the shape of the membrane by shaping the inner membrane of the gas storage depending on the amount of gas. When the storage tank is filled, the rope follows the spherical shape of the inner membrane and uses the longest rope length. In the empty state, a relatively flat rope position can be seen and the smallest rope length is exposed. The resulting rope length change is transmitted to the external counter mass and results in the vertical position change of the mass depending on the filling level. The filling level value can be detected by different measuring variants of the counter mass position detection or the rope length change outside the support air compartment. This is possible, for example, by means of an ultrasound sensor that permanently measures the distance (clear internal distance between mass and sensor) of the counter mass in a vertical guide tube.

Internal gas storage pressure measurement system

In this system, the internal gas storage pressure is recorded as a measure of the gas storage filling level. This system is suitable for gas storage types that achieve an increase in the internal gas storage pressure with the increase in the quantity of gas captured. As described under the section “Characteristic curve of the filling level measurement system” this system is not suitable for pneumatically preloaded gas storage systems with a constant pressure curve as the gas quantity increases.

Technical requirements, state variables, influencing factors

The requirements for gas storage systems are higher in the context of demand-driven biogas production and supply than in the normal operation of a conventionally operated biogas plant with constant on-site electricity generation. A measuring system to determine the gas storage filling level must be available, which is suitable for the type of construction used and has a sufficient accuracy and the ability to document the measurements. That means the measurement accuracy must be in a range that allows detailed statements to be made for the operational management of the system. The filling levels should be verifiable by means of persistent recording, storage and processing of the measured values. The storage facility must be designed to cope with the biogas production rate, weather conditions and the variable utilisation and gas quantity required for the purpose of variable biogas production and supply, and must be designed to be operationally reliable. The feed-in and feed-out of biogas plays an important role in the gas storage system, since, in contrast to conventional plant management, operationally high and short-term volume flows occur and process-safe operation must be ensured. If several gas storage facilities are interconnected, it must be ensured that the storage filling levels are standardised in order to minimise losses and make the entire storage capacity available (Kube 2018). A high level of system tightness and the avoidance of ignition sources are necessary for safe and efficient operation. Protection against overpressure and underpressure in the gas storage area and an adequately designed support air supply for pneumatically preloaded gas storage systems must be ensured (Stur 2018). The overview in Table 1 lists the general requirements for biogas storage systems based on the DWA-M 377 code of practice (Fachverband Biogas e.V. et al. 2016).

Table 1: Overview of the general requirements for biogas storage systems based on Code of Practice DWA-M 377 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2016)

General requirements for biogas storage systems
High storage capacity of approx. 12 h (Mauky et al. 2015; Barchmann et al. 2016)
Verifiability and documentability
Filling level measurable to a sufficient extent
Low level of gas permeability (methane permeation of membrane storage systems made of e.g. EPDM or PVC-coated polyester fabric < 500 mL (m^{-2} d^{-1} 1,000 hPa^{-1}) here deviating from DIN 1343 at 23 °C (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2017)
Odour-proof
Gas storage tightness
Weather-resistance (temperature and uv-resistant, wind, rain and snow loads due to material strength and design, guaranteed mobility of system components in the event of frost)
Resistant to herbal residues such as foliage
Protection against gas overpressure and underpressure events
Chemically resistant to trace gases, reaction products such as acids or elemental sulphur
Biologically resistant to microorganisms
Mechanically resistant to loads such as tension, pressure and creasing (risk of kinking, tearing), chafing and jamming (e.g. by rope)
Flame retardant
Electrical discharge capacity (ignition source avoidance)
Dealing with occurring gas volume flows (maximum production, feed-out)
Operational in combination with several switched gas storages
Application-specific design of the support air supply with damper flap

State variables

During the investigations, the following state variables were identified:

- Pressure $\mathbf{p}$ in hPa
- Volume flow $\dot{\mathbf{V}}$ of the gas and substrate quantities in m^3 h^{-1}
- Temperature $\mathbf{T}$ in °C
- Gas storage volume $\mathbf{V}_{GS}$ in m^3 (e.g. for gross, net or support air volume)
- Gas storage filling level $\mathbf{L}_{GS}$ in % or m^3
- Relative humidity $\boldsymbol{\varphi}$ in %
- Gas concentration $\mathbf{c}$ in %
- CHP firing thermal output $\mathbf{P}_{FWL}$ in kW

Influencing factors

When determining the net gas storage capacity, factors such as

- volume flow measurement (measurement technical design)
- weather conditions, see section „Influence of weather conditions on net gas storage capacity"
- temperature
- pressure in the gas storage
- gas production in the fermentation tank
- feed-in and feed-out of the fermentation medium (feeding and filling level of fermentation medium)
- efficiency of the conversion unit

- load condition of the CHP units combustion engine
- use of additional operating resources such as ignition oil
- duration of gas supply (feed-out duration during test)

have an impact on the result.

The gas temperature and the associated gas density, the efficiency of the conversion unit like the CHP unit as well as the gas production can only be determined to a limited extent. However, this circumstance is comparable to the real conditions at practical plants due to the low level of measurement equipment and the narrow scope for carrying out experiments in normal operation in terms of operational organisation. Thus, a compromise must be found between the applicability of the method on a biogas plant and the accuracy.

The aims of this publication are therefore:

- Comparison of three methods for practical determination of the usable volume or storage capacity of gas storage systems,
- Comparison of different gas storage filling level measurement systems and
- investigating the influence of weather conditions on gas storage capacity.

Material, methods and implementation

In this chapter the used devices and methods are presented.

DBFZ Research Biogas Plant

The DBFZ research biogas plant (RBP) is located on the premises of the DBFZ – Deutsches Biomasseforschungszentrum gemeinnützige GmbH in Leipzig, Germany. The two central stirred main fermentation tanks of the RBP have a working volume of max. 190 m^3 each. In addition, a plug flow reactor (53 m^3 working volume), an optional pre digester (88 m^3 working volume), a post digester (215 m^3 working volume), a manure storage (174 m^3 reaction volume) and a digestate storage (215 m^3) are available. The post digester and the digestate storage are equipped with a double membrane gas storage. Figure 3 shows the structure of the post digester with integrated pneumatically preloaded double-shell membrane gas storage, which was investigated in this study. There is an ignition jet engine CHP unit with a rated electrical capacity of 75 kW (Table 2) and a gas flare for biogas utilisation on site. Figure 4 provides an overview of the measurement technique used.

Table 2: Overview of the measurement technique used

Application	Measuring principle	Measuring range
Measuring section gas quantity & volume flow (MS1 and MS6) [1)]	Differential pressure, dynamic pressure probe with transmitter	4 to 20 mA, 0.02 to 2.53 hPa, 1.03 to 11.86 m s^{-1}, 8.7 to 100 m^3 h^{-1}
Measuring section gas quantity & temperature (MS1 and MS6) [1)]	PT 100	4 to 20 mA, -50 to 50 °C
Measuring section gas quantity & absolute pressure (MS1 and MS6) [1)]	Pressure transmitter	4 to 20 mA, 0 to 2,500 hPa
Temperature in the gas compartment & liquid phase (MS2, MS3 and MS4) [1)]	PT 100	4 to 20 mA, 0 to 100 °C
Pressure in gas storage (MS5) [1)]	Pressure transmitter	4 to 20 mA, -25 to 25 hPa
Fermentation medium filling level (MS8) [1)]	Hydrostatic, pressure transmitter	4 to 20 mA, 10 to 1000 hPa,
Gas storage filling level (MS5) [1)]	Displacement measurement, ultrasound	4 to 20 mA, 0 to 3.5 m
Gas storage filling level (MS5) [1)]	Hydrostatic, pressure transmitter	4 to 20 mA, 0 to 1000 hPa, 0 to 9 m
Pyranometer, Solar radiation (weather station) [1)]	thermopile	-200 to 2000 W m^{-2}
Multi-weather sensors Wind speed Wind direction Precitipation Illuminance, Temperature Air Humidity Air Pressure (Weather Station) [1)]	 Ultrasound Ultrasound Doppler radar Photo sensor Integrated hydro-thermosensor Integrated hydro-thermosensor Piezo-resistive pressure sensor	 0.01 to 60 m s^{-1}, 0 to 360°, 0.001 to 100 mm h^{-1} 1 to 150 lux -40 to 80 °C, 0 to 100% relative humidity 300 to 1100 hPa

[1)] Measuring point name, position of the measuring points shown in Figure 4

For balancing the gas quantities entering and leaving the gas storage (reference method), there is a gas volume flow measuring section at the inlet and outlet. The measuring sections consist of a dynamic pressure probe, a temperature sensor and an absolute pressure sensor. A gas sampling point is located in the measuring section, where samples are taken automatically. The gas composition is determined in a gas analysis system. The measuring sections are completely enclosed, insulated and equipped with trace heating to avoid inaccuracies due to external environmental influences. Inside the gas storage, the relative pressure and the gas temperature are recorded. The filling level of the fermentation medium is determined hydrostatically by means of a reference pressure sensor (Table 3).

Table 3: Technical data CHP-unit (ignition beam) assuming full load operation – manufacturer´s data

Parameter	Value
Firing thermal output	187 kW
Electric power	75 kW
Thermal output	70 kW
Electrical efficiency	40%
Thermal efficiency	37,5%
Ignition oil consumption (RME)	1 – 2 L h^{-1}

In order to investigate the measurement behaviour of the gas storage filling level more precisely, the existing measurement technology was expanded. The rope pull measurement system consisting of one rope pull was extended to 6 rope pulls offset by 60°. The ropes are equipped with variably adjustable masses. One end of the ropes is not attached to the edge of the tank, as it is usually the case, but runs radially outwards from the pole cap of the gas storage inner membrane. The change in length is continuously recorded by an ultrasound sensor in the case of three wire rope hoists offset by 120°. For the other three rope pulls, a discontinuous, manual reading is possible on a scale located on the guide tube. In addition, two flexible tube scales are mounted opposite each other on the gas storage membrane. Figure 5 shows the position of the measuring systems in plan view.

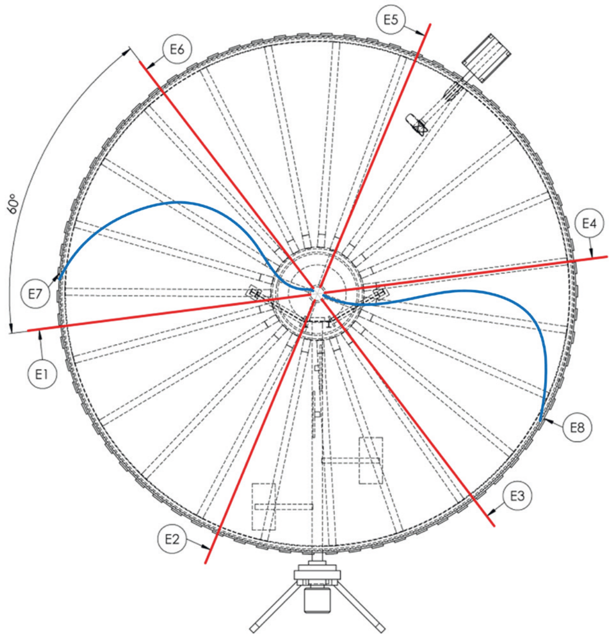

Figure 5: Top view of the gas storage roof; E1 to E6 position/route of the individual rope pulls of the rope pull measurement system in red; E7 and E8 position/route of the flexible tubes of both hydrostatic pressure measurement systems in blue

To investigate the weather influence on the gas storage behaviour, a combination weather measuring station was installed, consisting of a pyranometer (Kipp & Zonen, SMP11) and a multi-sensor unit (RTS Automation Vertriebsgesellschaft, Clima Sensor US NHTFB). The gas storage is equipped with a pressure relief valve based on the principle of a water cup. This is triggered at a relative negative pressure ≤ -2.5 hPa and at a relative positive pressure > 5 hPa.

The gas storage is checked for leaks using the following procedures. Once a year, the connection clamping ring between the container and the gas storage is sprayed with a foam-forming agent in order to detect any gas leaks in this area due to possible bubble formation. In addition, the gas storage is scanned with an infrared camera for this purpose. Once a day, the methane concentration in the support air is determined with a methane-sensitive measuring device at the outlet of the support air.

Methods for volume and capacity determination

One of the objectives of this study is to determine influences on biogas storage operation and to compare three methods for determining the volume of pneumatically preloaded integrated double-shell membrane gas storage systems and their performance in terms of net gas storage capacity for biogas. For this purpose, the following three methods are compared (Figure 6):

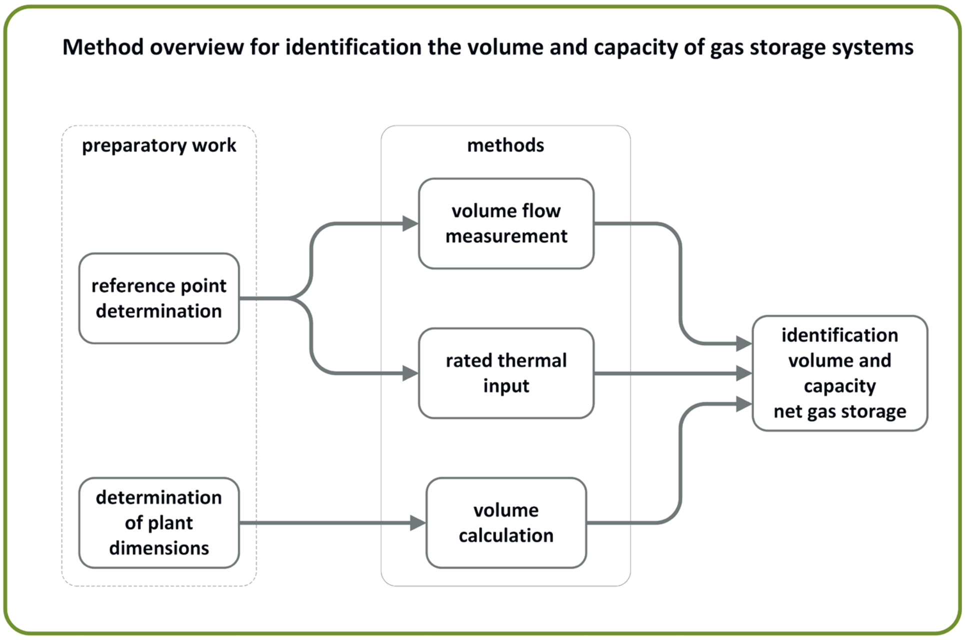

Figure 6: Overview of three methods to determine gas storage capacity and volume

M1 volume flow measurement – methodically extensive reference method for determining the net gas storage capacity

M2 firing thermal output – practical, methane consumption-based method for determining net gas storage capacity

M3 volume calculation – theoretical calculation method for determining the net gas storage volume.

Method M1 – volume flow measurement

To determine the net gas storage capacity using the biogas volume flow measurement method, the double membrane gas storage of the post digester is filled starting from a technically empty state and transferred to a technically full state. Finally, the gas storage is returned to the technically empty state. In order to be able to create measurability, transferability and reproducibility, two reference points for the technically empty and technically full state of the integrated gas storage are first described and verified by measurement. The two reference points cover the entire range of the net gas storage capacity. By recording the feed-in and feed-out biogas volumes V_{in} and V_{out} using the volumetric flow sensors MS1 and MS6, their difference (Equation 1, Table 4), with reference to the recorded volume, and the test duration of the individual phases, a specific biogas production rate $\dot{V}_{BB}$ is determined, see equation 2. Taking into account the duration for the respective phases of pause and feed-out, the quotient of the specific biogas production rate and these two added durations is used to record the amount of biogas

$V_{BB,P,A}$ produced during the pause and feed-out in equation 3. By subtracting the biogas quantity $V_{BB,P,A}$ from the feed-out volume V_{out} in equation 4, the net gas storage capacity $K_{GS,N}$ is determined.

$\Delta V = V_{out} - V_{in}$	Difference between the volume of biogas feed-out and feed-in	(Eq. 1)
$\dot{V}_{BB} = \frac{\Delta V}{t_G}$	Specific biogas production rate in the fermentation tank	(Eq. 2)
$V_{BB,P,A} = \frac{\dot{V}_{BB}}{t_p + t_A}$	Volume of biogas produced during pause and feed-out	(Eq. 3)
$K_{GS,N} = V_{out} - V_{BB,P,A}$	Net gas storage capacity	(Eq. 4)

Procedure for determining the reference points

The aim of this investigation is the description and the measurement of the reference points for the state technically empty and the state technically full of the integrated gas storage of the RBP.

The test is divided into 2 phases for mapping the two gas storage states technically empty and technically full. For future transferability to other practical plants, it is important to carry out the test in accordance with the normal operation of the plant. In phase 1, the state is technically full. Similarly, the technically empty state is set in phase 2. The requirements for the plant to be investigated are listed below:

- Internal gas storage pressure measurement with an accuracy of at least 0.1 hPa and an interval time of at least 5 s
- Check the settings of the overpressure and underpressure protection (limit value for automatic triggering of the overpressure and underpressure protection in the underpressure event at prel ≤ -2.5 hPa and in the overpressure event at prel > 5 hPa)
- Gas line circuit with exclusive feed-out of the raw biogas in the gas storage directly into a conversion unit
- Ensuring that the amount of electricity generated during CHP operation can be documented
- Volume flow measurement of the feed-in or feed-out raw biogas volume in the gas storage
- Biogas temperature measurement
- Constant fermentation medium filling level in the fermentation tank
- Analysis of biogas concentration, especially methane and carbon dioxide, by gas analyser

Phase 1 – Setting the reference point technical empty

During phase 1, the entire raw biogas flow produced is fed from the other fermentation tanks into the second gas storage of the digestate storage. Under full load, the conversion unit extracts the biogas required for operation from the gas storage of the fermentation tank and thus empties the filled storage tank. When the internal gas storage pressure drops to 0.5 hPa, and the gas storage inner membrane slightly penetrates on the belt support system during the visual inspection at the sight glass of the outer membrane, the conditions for the state technically empty for the gas storage are fulfilled. Thus, the reference point technical empty is described and verified by the system and measurement.

Phase 2 – Setting the reference point technical full

In phase 2, the entire produced raw biogas is fed into the gas storage of the fermentation tank. All other gas-carrying fittings of the fermentation tank are closed so that no gas escapes from the gas storage. At the end of filling, the internal gas storage pressure must reach the value of 4.5 hPa and should not exceed this value. For support, the course of the internal gas storage pressure is consulted. From the moment the gas storage pressure leaves the constant curve, it can be concluded that the calotte-shaped storage membrane is completely filled. After the visual inspection through the sight glass integrated in the outer membrane, the gas storage membrane must be completely in contact with the sight glass. If these conditions are fulfilled, the reference point technical full is achieved and proven.

Method M2 – firing thermal output

In this method, the electrical active energy W_{el} generated during the test period is recorded in order to be able to conclude a biogas consumption using an assumed electrical efficiency η_{el} of the conversion unit, the consumed ignition oil quantity V_Z, as well as the heating value for methane $H_{i,M}$, ignition oil $H_{i,Z}$ and the measured methane concentration c_M in the biogas. The biogas consumption can then be used to determine the biogas quantity V_{BG} and the net gas storage capacity $K_{GS,N}$. Equation 5 is used to calculate the biogas quantities consumed.

$$V_{BG} = \frac{\left(\frac{W_{el}}{\eta_{el}}\right) - (V_Z \cdot H_{i,Z})}{H_{i,M} \cdot c_M} = K_{GS,N} \qquad \text{(Eq. 5)}$$

When the biogas is feed-out from the gas storage, the CHP unit must be in a warmed-up operating state. This ensures that no biogas consumption values deviating from normal operation (cold start phase) are recorded. For this purpose, a gas buffer separate from the gas storage is required on the biogas plant to be investigated. On the other hand, it is necessary to be able to set up a pipe connection that does not allow simultaneous parallel biogas feed-out, e.g. by further conversion units from the gas storage during the test phase.

Method M3 – volume calculation

In order to create the basis for comparability and to implement a plausibility check of the measured values, a theoretical determination of the gas storage volume in the standard state is carried out (Deutsches Institut für Normung e.V. 1990). The following assumptions are made: No suitable measurement procedures are available for the exact description of the shape of the gas storage inner membrane in the technically empty or full state. The shape of the membrane is therefore described by taking into account empirical values and the determination in a 3D CAD system. The course of the belt of the belt support system in the axially symmetrical section starting from the fastening ring of the support column to the upper edge of the tank shell plays an important role. The lower area of the net gas storage volume is determined by the hyperboloid shape of the belt support system. Further details are taken from the planning documents.

The parameters and equations for calculating the volumes are shown below:

d	Inner diameter of fermentation tank
$h_{K,S}$	Clear internal dimension between fermentation medium level and calotte of the gas storage inner membrane
h_K	Height of the calotte of the gas storage inner membrane
V_Z	Volume of the cylindrical tank gas area
V_H	Volume of the hyperboloid
V_K	Volume of the calotte of the gas storage inner membrane in the technically full state
$V_{GS,B}$	Gross gas storage volume
$V_{GS,N}$	Net gas storage volume
$V_{GS,K}$	Temperature and pressure corrected net gas storage volume
p_N	Standard pressure (1013.25 hPa)
T_N	Standard temperature (273.15 K)
p_{mess}	Measured pressure
ϑ_{mess}	Measured temperature
p_W	Partial pressure of the water vapour
A, B, C	Parameters of the Antoine equation

$$V_K = \pi \frac{{h_K}^2}{3}(1.5\,d - h_K)$$
Volume of the calotte (calotte-shaped gas storage inner membrane) (Eq. 6)

$$V_Z = \frac{\pi}{4} d^2 \cdot h_{K,S}$$
Volume of the cylindrical container gas area (freeboard) (Eq. 7)

$$V_H = V_K \cdot 0.045$$
Volume of the hyperboloid in the technically empty state, determined by the 3D CAD system. (Eq. 8)

$$V_{GS,N} = V_K - V_H$$
Net gas storage volume (Eq. 9)

$$V_{GS,B} = V_K + V_Z$$
Gross gas storage volume (Eq. 10)

$$V_{GS,K} = \frac{V_{GS,N} \cdot p_N \cdot (\vartheta_{mess} + 273.15\,K)}{(p_{mess} - p_w) \cdot T_N}$$
Temperature & pressure corrected net gas storage volume (Eq. 11)

$$p_w = 10^{A - \frac{B}{C + \vartheta_{mess}}}$$

with: A = 7.19621
B = 1730.63
C = 233.436

Partial pressure of water vapour using the Antoine equation (Eq. 12)

Results and discussion

In this chapter, the results of the methods M1 to M3 are shown and discussed in their application. Furthermore, the display behaviour and the suitability of the investigated gas storage filling level measurement systems are presented and weather-related influences on the gas storage operation and the net gas storage capacity are analysed.

Comparison of methods for volume and capacity determination

After carrying out the method M1 volume flow measurement, the values of the volume flow measurement on the inlet and outlet side were documented with reference to the gas volume. 131.5 m^3 of raw biogas (V_{in}) were recorded during the feed-in of the raw biogas into the gas storage. The duration t_E was 3 h and 30 min. During the feed-out process (V_{out}), 142.0 m^3 were measured with a feed-out duration t_A of 3 h and 28 min. The total test duration t_G, including a pause time t_P of 19 min between the feed processes, which was necessary for adjustment work such as valve actuation and CHP connection, was 7 h and 17 min. The difference ΔV of both volume measurements is, in addition to the measurement accuracy of the volumetric flow sensors, decisively attributed to the permanently continuing biogas production in the fermentation tank. According to equation 1, ΔV corresponds to 10.5 m^3 and the resulting specific biogas production rate $\dot{V}_{BB}$ results in 1.45 $m^3\ h^{-1}$ using equation 2. If the pause and feed-out times are combined, inserting the values in equations 3 and 4 results in a net gas storage capacity of $K_{GS,N}$ = 136.5 m^3.

With regard to the practicality of this method, a pause duration of less than 30 min is favoured. Depending on the exceeding of the reference point technical full, the danger of triggering the pressure relief valve is also pointed out. By reducing the pause duration t_P, the resulting biogas production is reduced to a low level and the accuracy of the test result is increased.

In the method M2 Firing thermal output that was carried out at the same time, all the biogas was fed directly to a downstream CHP unit while the biogas was being fed out of the gas storage. The effective energy W_{el} determined in this process was 259 kWh. The amount of ignition oil V_Z consumed was 4.7 L. The averaged methane concentration c_M in the biogas was 49.7%. The efficiency η_{el} of the CHP was assumed to be 36.9% using the factory data from Table 3 and a deduction of 3.1% (Fachagentur Nachwachsende Rohstoffe e.V. 2021). By using equation 5, the net gas storage capacity is $K_{GS,N}$ = 133.0 m^3. With the transferred result of the net gas storage capacity from method M1, an efficiency of 36.0% would result and is 0.9% below the assumed value of 36.9%.

The result is thus strongly dependent on the value of the efficiency and the methane concentration in the biogas. To classify the values, the following Figure 7 shows the dependence of the calculated net gas storage capacity on an assumed electrical efficiency η_{el} of the RBP´s CHP unit of 36.9%. The challenge here lies in the resilience of the real efficiency value of the on-site CHP unit as well as in the unknown efficiency loss over the operating time of the CHP unit. This depends on various influencing factors, such as the operating hours, the quality of the operating equipment and the maintenance measures carried out (Aschmann and Effenberger 2012). The load condition of the CHP unit also has a considerable influence on the electrical efficiency. For example, it decreases in partial load operation, which has increased in its application in the context of flexibilised energy provision during start-up and shutdown processes.

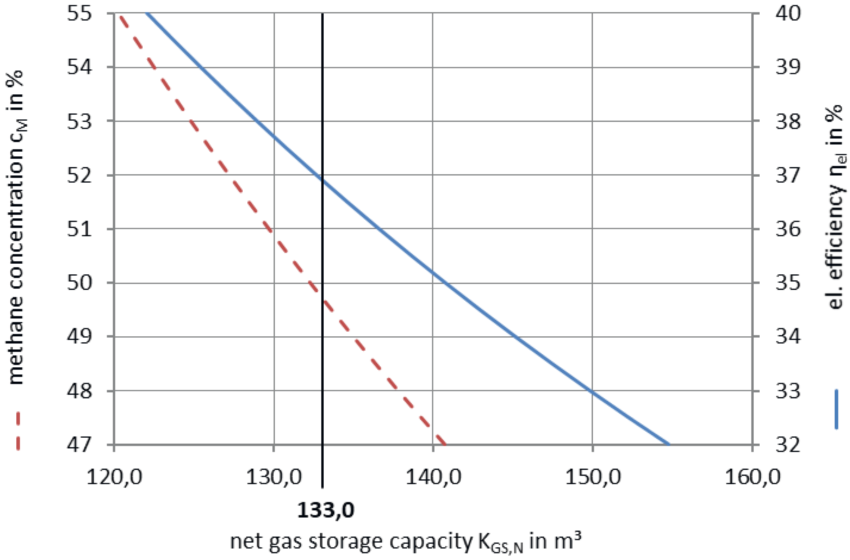

Figure 7: Representation of the range of the determined net gas storage capacity depending on an assumed methane content cM of 49.7 Vol.-% and electrical efficiency ηel of 36.9% of the RBP-CHP unit; change in the net gas storage capacity with varying methane content (red dashed line) or varying efficiency (blue)

In addition to the efficiency, the dependence of the net gas storage capacity on the variable methane concentration is also given in Figure 7. Due to the interval-based recording, the methane concentration is only measured approximately in practical plants. Thus, the resilience of this value can be assumed to be low, comparable to the efficiency. Calculating the net gas storage volume using the M3 volume calculation method results in a net gas storage volume of $V_{GS,N}$ = 144.5 m^3.

A clear distance between the outer membrane and the gas storage inner membrane of 400 mm from the planning documents was assumed. For the hyperboloid area of the belt support system, a volume of 4.5% of the spherical calotte-shaped area of the gas storage inner membrane was selected and determined by using a 3D CAD system. These values have a relevant influence on the result of the net gas storage volume. In a practical system, these values can hardly be verified with regard to the real design, in particular the shape of the gas storage inner membrane and its calotte shape accuracy and the course of the belts of the belt support system with the existing hyperboloid shape.

A conversion to the test conditions (average gas temperature during the test of 31.4 °C at 1013.25 hPa) results in a 14.4% lower net gas storage volume of 123 m^3 in relation to the geometrically calculated volume (Equations 11 and 12). With reference to the measured maximum value (39.4 °C) on the test day, the real gas storage volume is reduced to 117.4 m^3. This corresponds to a volume reduction of 18.7%.

The difference between the results of method M3 and the other two methods M1 and M2 may indicate deviations between the planning documents and the final implementation status. Due to the aforementioned difficulty in verifying the exact dimensions of the gas storage shape, this method turns out to be inaccurate for this specific example.

Characteristic curve of the filling level measurement system

As part of the investigation of the process parameters of the gas storage during the determination of the reference points, three filling level measurement systems were evaluated, see section “Methods for volume and capacity determination”. The results are shown in Figure 8. The two red graphs show the constant feed-in and feed-out of biogas. The blue graph in Figure 8 shows the characteristic curve of the gas storage internal pressure of the double-shell pneumatically preloaded gas storage. After leaving the reference point technical empty on the left of the diagram, there is a strong increase in pressure due to the biogas feed-in up to a first plateau at 3.3 hPa. Up to this plateau, the biogas accumulates in the gas compartment without any significant increase in the form of a slight compression from 0.5 to 3.3 hPa. From this point, the vertically aligned shaping of the gas storage inner membrane begins. This is followed by a constant pressure curve until the fully shaped state of the gas storage inner membrane is reached. From this moment on, there is an isochoric space and the internal gas storage pressure increases rapidly due to the further feed-in of biogas. When it passes 4.5 hPa, the reference point technical full is reached and the biogas feed is stopped. When switching between filling and emptying, care was taken to ensure that no overpressure greater than 5 hPa was set in order to avoid triggering the pressure relief valves and the associated loss of raw biogas. After switching to gas storage emptying, the pressure drops from 4.5 to 2.8 hPa can be seen due to the feed-out of the biogas. In contrast to filling, a lower pressure level of 2.8 hPa is visible during the constant pressure curve. This is caused by the CHP biogas consumption and the generated outlet underpressure of the gas compressor after the gas conditioning module. Finally, the pressure drops sharply to 0.5 hPa shortly before reaching the reference point technical empty.

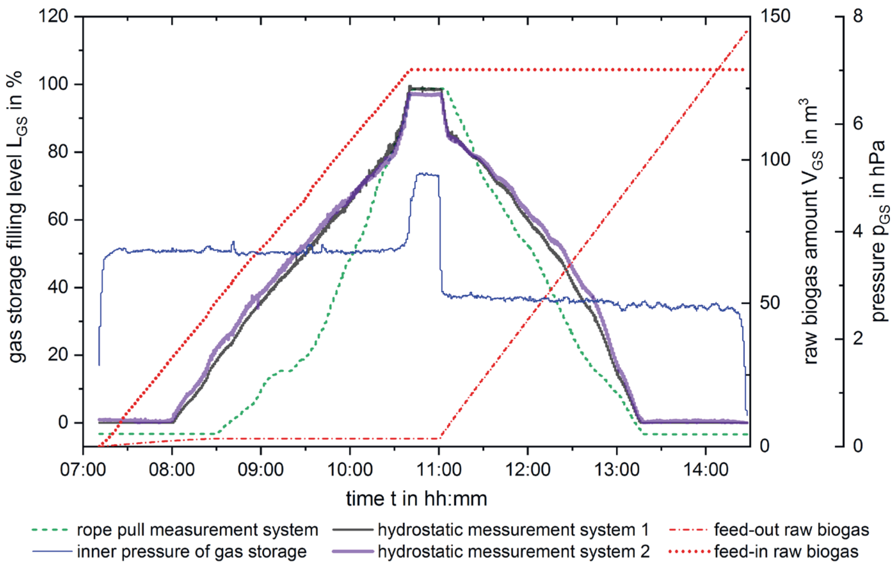

Figure 8: Representation of the characteristic curve of the integrated double-shell pneumatically preloaded membrane gas storage of the fermentation tank

A delayed detection of the filling level change can be seen with both the rope pull and the hydrostatic pressure measurement system. This is due to the undefined shape of the inner membrane of the gas storage during the biogas increase and the partial scanning of the surface of the inner membrane of the gas storage by the rope pulls or the flexible tubes. This dead band during gas storage filling is approx. 39% for the cable measurement system and approx. 24% for the hydrostatic pressure measurement system in relation to the recorded biogas feed quantity. The offset can be caused by the different positioning of the measuring elements and the partial membrane deformation (Figure 3). During the emptying process, the detection of the filling level change ends at approx. 35% residual level in relation to the biogas feed quantity. From this, an unsuitable display behaviour of the two measuring systems can be derived in the lower filling level range of the gas storage. In the middle and upper filling level range a comparable curve to the feed-in flow can be seen. It is not possible to determine the filling level via the internal pressure of the gas storage due to the constant pressure curve over the entire filling or emptying process for technical reasons. For the detection of the reference points, however, the pressure is of great importance. Thus, the gas storage internal pressure measurement system is not suitable for continuous measurement of the filling level in this gas storage design.

During the investigations of the filling level measurement procedures and the observations of the gas storage membrane shaping, the positional accuracy of the pole cap was additionally monitored. This was done with the help of the six cable pulls attached to the pole cap and aligned radially, and by comparing the vertical position of the counter masses in the guide tubes in relation to the filling level, especially in the area of the reference points. A very high repeatability of the pole cap position in the technically full state could be detected due to the fully formed and defined shape of the spherical calotte. When the gas storage inner membrane was placed on the support column in the reference point technical empty, no reproducible pole cap position could be achieved. The causes for the pole cap drift are assumed to be, amongst others, the undefined folding of the membrane, the variable fluidic conditions in the gas storage interior and the uneven weather influences such as wind and solar radiation.

Influence of weather conditions on net gas storage capacity

Figure 9a shows an example of the course of the measured variables global radiation, wind speed and ambient temperature and pressure over a period of three days. Days 1 and 3 were cloudy, whereas day 2 had mostly clear skies. This can also be seen in the clear change in direct solar radiation, which is also expressed in the increase in ambient temperature.

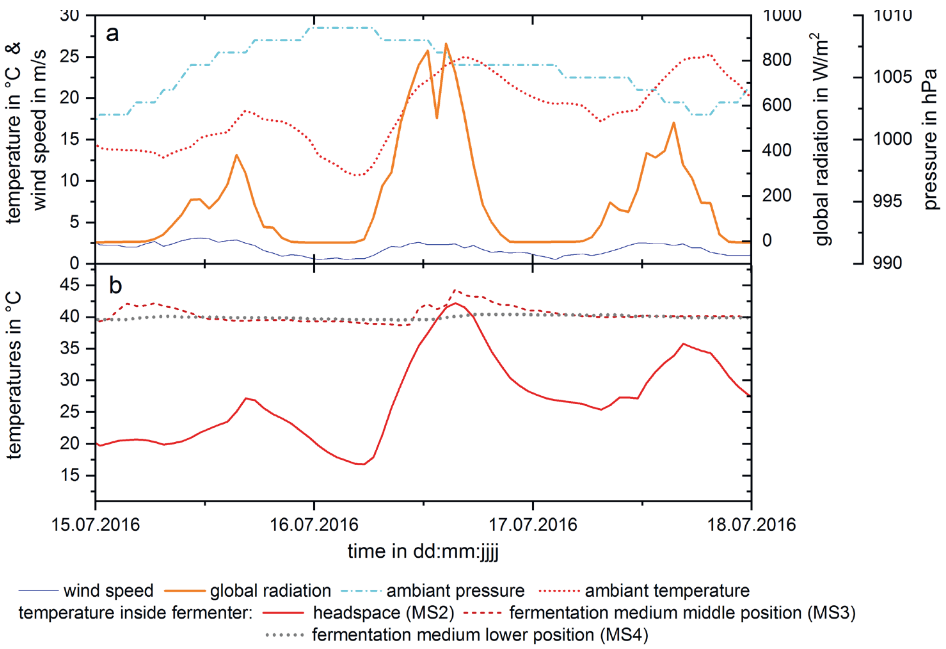

Figure 9: Influence of weather conditions on the course of temperatures in the gas storage and fermentation medium

Figure 9b shows selected temperature curves in the fermentation tank (post digester of the RBP) and gas storage. Furthermore, the temperature in the lower area of the fermentation tank and the temperature in the middle of the tank, which is located close to the tank heating is plotted. It can be seen that the temperature in the gas compartment undergoes significant changes depending on the weather conditions. There is a clear cooling, especially at night and on the first day. In the morning of the second day, the internal gas storage temperature increases significantly as a result of the strong solar radiation and increased outside temperature up to the fermentation medium temperature. During this test period, the fermentation medium was only mixed intermittently with low intensity. As a result, a reduced heat transfer in the direction of the gas phase through the liquid phase can be assumed. Table 6 describes selected parameters and meteorological influencing variables with regard to their effect on the internal gas storage temperature.

Table 6: Important variables influencing the internal gas storage temperature.

Parameter	**Description of the influence on the heat balance of the gas storage**
Solar radiation	Heating of the weather protection membrane, convective heat transfer as well as heat radiation via inner membrane
Outdoor temperature	Cooling or heating, depending on the temperature gradient to the gas storage temperature
Wind speed	Cooling of the weather protection membrane
Rain	Cooling of the weather protection membrane
Snow	Insulating effect on weather protection membrane
Cloud cover	▪ Clear sky → Heat radiation between the weather protection membrane and the sky is higher, tendency to increase cooling; under the rather dry winter conditions this effect can be even more pronounced ▪ Cloudy sky → Lower temperature difference between weather protection membrane and sky (water vapor in the form of clouds, i.e., the decisive factor here is the dew point temperature), leads to reduced cooling by radiation
Temperature fermentation medium	Heating the biogas to the temperature of the fermentation medium
Mixing fermentation medium	▪ Good mixing → Turbulence enables high heat transfer between fermentation medium and gas phase ▪ Little to no mixing → Low turbulence in the liquid phase leads to reduced heat transfer to the gas phase; resulting Floating layers act as additional heat insulator towards gas phase

The measurements carried out at the RBP show intraday fluctuations of the internal gas storage temperature of up to 30 K. In order to describe the effects of this temperature change on the available gas storage volume, the ideal gas law, supplemented by the water vapour component, was used (Equations 11 and 12).

Figure 10 shows the calculations related to a measured temperature curve, which was scaled on the basis of 3 temperature gradients (ΔT = 10, 20 and 30 K). Depending on the initial level of temperature change, this results in up to 20% less available storage volume.

To compensate for the temperature influence on the available storage capacity, there exist two possibilities:

1. Static variant: For the temperature correction in the capacity determination (equations 11 and 12), an internal gas storage temperature of at least 50 °C (maximum gas temperature measured at the RBP in the gas storage) is assumed approximately (or the maximum temperature measured at the respective gas storage to be corrected). The resulting corrected gas storage capacity is statically set as the maximum available volume. As a result, storage potential remains unused during phases of lower temperatures, but overpressure events caused by high temperatures are avoided.
2. Dynamic variant: The internal temperature is permanently monitored and used for a correction of the display value. This would allow for dynamically released storage capacities at lower temperatures to be used and yet avoid overpressure situations at higher temperatures.

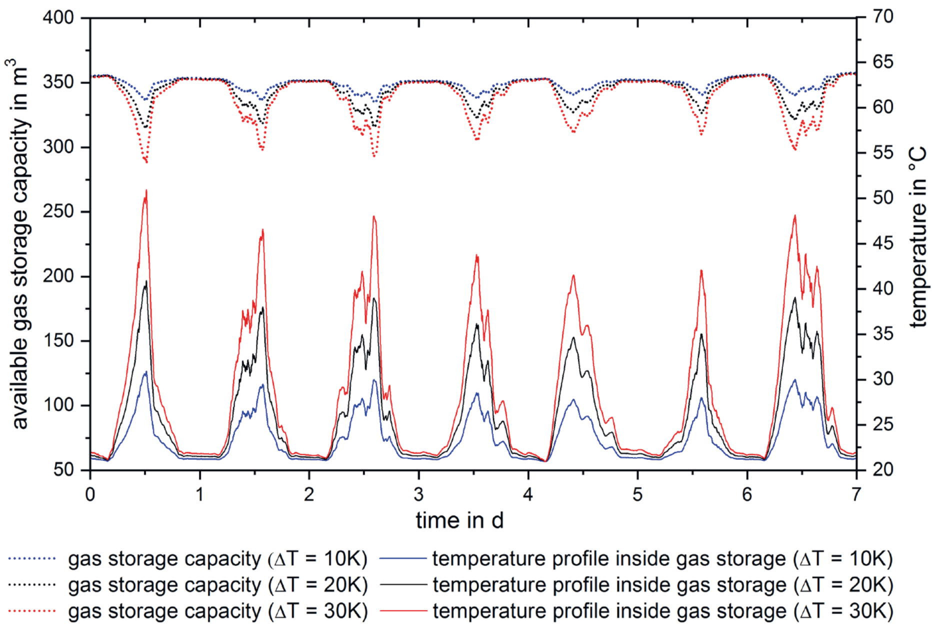

Figure 10: Mathematical illustration of the influence of the internal gas storage temperature on the available gas storage volume at different temperature spreads

Especially in the context of flexibilisation, anticipatory planning of the operation is important (Mauky et al. 2015). This would then require a forecast of the biogas temperature inside the storage tank, which depends in particular on the ambient conditions (for example weather and fermentation tank heating) and the structural design of the storage tank. The respective thermodynamic processes could be mapped in a calculation model, which could then be combined with predictive feeding and operational planning (Mauky et al. 2016). A further advantage of such a model-based system would be the balanced estimation of the gas storage filling level in areas of insufficient accuracy of measurement systems, especially in areas of filling levels below 40%.

Conclusions

Within the scope of the investigations of the gas storage, state variables and influencing factors are identified and the effects of relevant variables are described. Limits in the display behaviour of gas storage filling level measurement systems are shown and the unsuitability of the gas pressure measurement system for continuous measurement of the filling level in a pneumatically preloaded double-shell membrane gas storage are demonstrated. Furthermore, the effects of weather-related influencing factors are illustrated and measures to avoid biogas emissions during normal operation of a biogas plant are presented. The operation of the gas storage in the range of 30 to 70% filling level represents a simple as well as effective measure to avoid release events with emissions of biogas due to unexpected temperature fluctuations. This range can be extended with the use of suitable measurement- and plant technology equipment.

Thus, through simple operational measures, such as an adapted operating regime, which ensures a maximum filling level of 70% especially before sunrise, undesired biogas emissions as well as biogas losses for the plant operator can be avoided without further investments in technical plant equipment. When comparing the methods for determining the volume and capacity of the gas storage, it is possible to find influential parameters that, depending on their availability, are significantly involved in the reliability of the result. E.g. the efficiency of the conversion unit, the methane concentration in the biogas, the measuring accuracy of volume flow meters or dimensions that show deviations from the planning data for the on-site execution of the manufacturing and installation work of the gas storage are possible influential parameters.

Particularly in the course of flexibilisation, the gas storages play a vital role as a link between generation and utilisation of biogas. In order to be able to use the gas storage optimally, it is important to increase the measurement accuracy, especially in the border areas. On the one hand, this can be achieved by improving measurement systems, e.g. by combining different measurement systems. On the other hand, the development of special cuts of the storage membranes could make the depositing and shaping of the membrane more consistent, which would reduce the pole cap drift and simplify the measurement with conventional systems. Another possibility to make better use of the available storage capacity would be the anticipatory temperature correction of the storage volume. This requires further investigations into the weather-related influencing variables, which would then serve as the basis for the thermodynamic description of the gas storage.

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Authors

Mathias Stur is a research associate, **Marcel Pohl** is a working group leader, **Christian Krebs** is the technical manager of the research biogas plant in the Biochemical Conversion (BK) – Biogas Technology Working Group and **Dr.-Ing. Eric Mauky** is a research associate in the Process Monitoring and Simulation Working Group, DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Torgauer Straße 116, 04347 Leipzig. Email: mathias.stur@dbfz.de

Note

All volume data for gases refer to the standard state according to DIN 1343.

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