Chapter 3
Biogas Plants: Design and Fabrication

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List of Abbreviations

BoP	Balance of Plant
CAPEX	Cost of investment
CSTR	Continuous stirred-tank reactor
FIT	Feed-In Tariff
HRT	Hydraulic retention time
MSW	Municipal solid waste
OFMSW	Organic fraction municipal solid waste
OLR	Organic loading rate
PGY	Potential Gas Yield
Q_D	Quantity of dilution
TDS	Total dissolved solids
TS	Total solid content
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket
VS	Volatile solids content

3.1 Plant Description

The structure of biogas plants is quite similar but the choices made during the design of the related details will be the key factors to lead a project to success (or not).

The typical configuration of a biogas plant consists of the followings areas:

1. Substrate management area (receipt, storage, transportation to feeding, etc.)
2. Feeding and/or pre-treatment area

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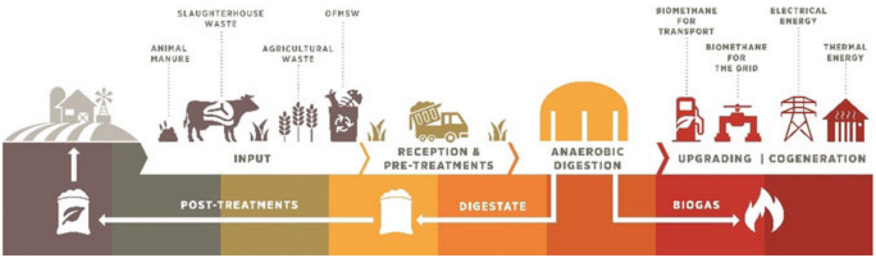

Fig. 3.1 Schematic presentation of the processes taking place in a biogas plant [SEBIGAS s.r.l.]

3. Anaerobic digestion area
4. Gas storage, treatment and usage
5. Digestate storage/usage/disposal

Materials flow through the different steps releasing their energy content in the form of biogas and are then extracted from the digesters, i.e., the digestate which could be disposed of or used as biofertilizer (Fig. 3.1).

Every step of the process needs to be carefully designed and evaluated, keeping in mind the final target of the project and it’s constrains. There is a huge quantity of different possible combinations of equipment, processes, and technics that can be applied to optimise a given plant and to create a successful project.

The best design is well associated with possessing a sufficient deal of experience in every single area mentioned above as well as the equipment used in the plant and moreover, with having an in-depth understanding on different parameters affecting the process and consequently the overall functionality, performance, and return of investment.

3.2 Basic Design

For designing an anaerobic digestion plant, it is important to accurately establish the volume of the digestion (single or multiple digesters) and this in turn could impact the fluid dynamics and speed of reaction.

The calculation of the volume is generally performed after deciding on the other configurations and operation conditions of the plant such as process temperature, number of stages/phases, as well as type of process and technology.

The main technical parameters based on which an anaerobic digester could be classified include:

- Solids content
  The digestion process can be usually divided from wet to dry digestion accordingly
- Temperature of digestion
  Psychrophilic, mesophilic, thermophilic

- Technology
  From batch process to continuous process (e.g., plug-flow, CSTR, UASB, lagoon)
- Number of stages/phases
  Single stage or double stage/phase

To be able to select the correct application, every biogas plant design should start from the selection and analysis of the feedstock available and its final usage. In fact, if the project analysis is initiated by taking into account other factors rather than feedstock analysis, loss of time and resources would be expected.

3.2.1 Substrate Characteristics

The knowledge required on substrate should not be limited to the time of analyzing the project, but rather, the best scenario is to have a complete picture of the situation faced by acquiring the following data:

- Available quantity of feedstock per year; per day and receiving frequency
- Quality of the feedstock in terms of TS, VS, gas yield, N content (TKN), S content, etc. as well as their potential variations
- Suggested HRT, OLR, and temperature of digestion

This chapter is not dedicated to the analysis of the biological quality aspects of feedstock, but mainly on the effects that the parameters involved have during the design phase of a biogas plant project.

Total solid (TS) is a key parameter to be analysed as it could lead to completely different technology selection and design criteria. For the design of a plant, it is important to understand not only the initial TS of the substrate, but also its degradability and accordingly, the final TS after anaerobic digestion. The TS content inside digesters is strictly related to the final TS calculation, while the feeding capacity/technics are related to the initial TS.

To calculate the final TS after digestion, it is necessary to evaluate the mass balance for the substrate considered (Eq. 3.1), therefore:

$$\mathrm{TS}' = \frac{\mathrm{TS} - \mathrm{TS} \times \mathrm{VS} \times \mathrm{PGY} \times \rho_{biogas}}{1 - \mathrm{TS} \times \mathrm{VS} \times \mathrm{PGY} \times \rho_{biogas}} \tag{3.1}$$

where:

TS'	Final TS concentration of the substrate after anaerobic digestion [%]
TS	Initial TS concentration of the substrate [%]
VS	Volatile solids concentration referred to TS [$\%_{\mathrm{TS}}$]
PGY	Potential gas yield [$\mathrm{Nm}^3_{\mathrm{biogas}}/\mathrm{t}_{\mathrm{VS}}$]
ρ_{biogas}	Specific weight of the biogas calculated as an approximation using the following formula (Eq. 3.2):

$$\rho_{biogas} = C_{\mathrm{CH_4}}\, x\, \rho_{\mathrm{CH_4}} + (1 - C_{\mathrm{CH_4}})\, x\, \rho_{\mathrm{CO_2}} \tag{3.2}$$

where:

C_{CH4} Percentage of CH_4 concentration in biogas
C_{CO_2} Percentage of CO_2 concentration in biogas
ρ_{CH_4} Specific weight of methane
ρ_{CO_2} Specific weight of carbon dioxide

As mentioned earlier, this value is an approximation because biogas contains other elements in small quantities (H_2S, H_2, O_2, N, etc.) as well that may slightly modify the final result.

The TS′ is basically lower than TS as a portion in form of VS is used by the microbial populations to produce biogas, and therefore the mass removed in form of biogas has to be removed through the mass balance calculations to determine the TS′.

TS′ concentrations below 2% would normally lead to the choice of a UASB or Lagoon system depending on the other biological parameters, while higher TS′ concentrations usually leads to the choice of CSTR technology (see paragraph 4.2.4.2) or even dry fermentation. In this chapter, the CSTR technology as the most common technology for industrial scale biogas plant is mainly analysed and discussed.

Hydraulic retention time (HRT) is the average time materials spend inside a digester and is calculated in day based on the substrate volume in input and digestion volume available (Eq. 3.3):

$$HRT = \frac{V_{net}}{Q_{sub}} \tag{3.3}$$

where:

V_{net} Available net digestion volume of the analysed system
Q_{sub} Volume of daily substrate input of the analysed system

Organic Loading Rate (OLR) represents the amount of volatile solids (kg) fed into the system analysed for every cubic meter of the available digestion volume every day. The OLR is therefore measured in $kg_{VS}/m^3/d$ as follows (Eq. 3.4):

$$OLR = \frac{Q_{VS}}{V_{net}} \tag{3.4}$$

where:

Q_{VS} Daily quantity of substrate volatile solids in the input of the analysed system

3.2.2 Process Temperature

Temperature of digestion is very important to finalise the design of a plant as a lot of components and equipment are affected by this parameter. In another word, the cost of the plant as well as the operation procedures may vary accordingly. In general, there are three different digestion temperatures:

Psychrophilic process is normally in use in lagoon systems while it is avoided in CSTR systems as it does not maximise the gas yield from the substrate and it is not easy to produce a constant quantity of gas out of the substrate either. The temperature range is usually considered lower than 25 °C, and therefore, there is no need for heating sources, however, the conversion efficiency of VS to biogas is lower than the other temperature regimes.

Mesophilic process is generally running smoothly and it does not require any particular attention for the selection of materials, it requires little thermal energy to keep the process temperature stable (especially compared with the thermophilic process). The temperature ranges between 37 and 42 °C.

Thermophilic process is “fast responding” to any modifications in the digestion parameters, which can lead to a more stressed operation of the plant and higher attention and effort would be needed to keep the same functionality. It should also be noted that the lifetime of some equipment (i.e. gasholder, mixers, pumps, etc.) could be negatively affected by high temperatures and hence, to keep the same reliability, the quality (and consequently costs) of the materials selected should be higher. On the other hand, this process usually allows the plants to operate at shorter HRTs at the same PGY rate due to the faster speed of reaction and therefore, the total digestion volume of the plant can be reduced.

In thermophilic processes, the speed of hydrolysis is normally 5 times higher the speed of mesophilic condition (Bouallagui et al. 2004; Converti et al. 1999). As a counter effect, the process is more affected by ammonia inhibition. Furthermore, the thermal energy need is sometime not affordable, especially with high moisture content substrates.

Overall and from the design and fabrication point of view, the main advantage of using a thermophilic process is the reduction of HRT. The temperature range is between 50 and 55 °C.

In general, different combinations of temperature regimes could also be used different in response to the specific case. For instance, a patented procedure by the Iowa State University (ISU) elaborated on the use of a thermophilic reactor to speed up the hydrolysis reaction in the first stage while a mesophilic reactor was used in the second stage to decrease the problems associated with ammonia inhibition and moreover, to have the possibility of using it as a back-up when encountering potential biological failures at the first stage (Han and Dague 1997).

The usage of intermediate temperatures between upper mesophilic limit (42 °C) and lower thermophilic limit (50 °C) could also be advantageous in terms of balancing the negative effects of inhibition caused by high temperatures and lower speed of reaction caused by lower temperature regimes.

It should be noted that rapid changes of temperature may damage and harm the microorganism, and therefore, the key issue during the design process regarding the temperature is not really to take necessary measures to ensure an exact temperature, but rather to prevent any fast temperature changes during the plant operation. In better words, if the temperature changes slowly in digesters, the existing microbial populations have the time required to adapt to the new situation without compromising the efficiency and the gas production.

3.2.3 Energy Outcome Target and Destination

The energy outcome target is basically established by the availability of substrate, the available size of the engine, the real need (or form) of energy production, and eventually by the limitations imposed by local authorities or feed-in tariff (FIT) policy.

As a general rule, the aforesaid feedstock parameters given at the time of the development of the project must be obviously taken into account, but precaution must be taken as they might easily change in time.

As the first step of calculation, it is possible to estimate the quantity of biogas that could be produced per year (Eq. 3.5):

$$Q_{biogas} = \sum_{i=1}^{n} Q_{sub_i} \cdot TS_i \cdot VS_i \cdot PGY_i \tag{3.5}$$

where:

N	Number of substrate used to feed the plant
Q_{biogas}	Quantity of biogas produced in a year [Nm^3/y]
Q_{sub}	Quantity of material available in a year [t/y]
TS	Initial TS concentration [%]
VS	Volatile solids concentration referred to TS [$\%_{TS}$]
PGY	Potential gas yield [Nm^3_{biogas}/t_{VS}]

Based on the expected percentage of methane content in biogas (based on the analysis of the substrate and its composition), it is possible to estimate methane production (Eq. 3.6):

$$Q_{CH_4} = Q_{biogas} \cdot C_{CH_4} \tag{3.6}$$

where:

Q_{CH_4}	Quantity of methane produced in one year [Nm^3/y]
C_{CH_4}	Concentration of methane expected in the biogas produced [%]

In case the biogas is converted into electricity and thermal power through a cogeneration system, the electrical power production can be approximated using the following formula (Eq. 3.7):

$$P_e = Q_{\mathrm{CH}_4} \cdot 10 \cdot n_e \tag{3.7}$$

where:

P_e Electrical energy produced per year [kWh/y]
n_e Electrical efficiency of the cogeneration system selected [%]

3.2.4 Digester Technology Classification

Based on the characterisation of the substrate to be treated, the investment capital availability, the target outcome power, etc., it is possible to select the technology of digestion that would better suite the need of the project.

Here is a summarized list of the different reactors technology available.

3.2.4.1 Batch Process

Usually identified as sequencing batch reactor (SBR), in this type of application, the reactor is loaded one time and all digestate/percolate formed during digestion is recirculated until the end of the cycle (Fig. 3.2).

This type of application has of course the disadvantages of a non-constant production of gas due to the different speed of reaction during the retention time and the gas production peaks at around 50% of the retention time.

In order to stabilise the process, it is normally suggested to operate with multiple reactors in parallel, with staggered cycles.

This process is usually applied for dry fermentation and it is associated with low operational costs in spite of high energy consumption and maintenance costs.

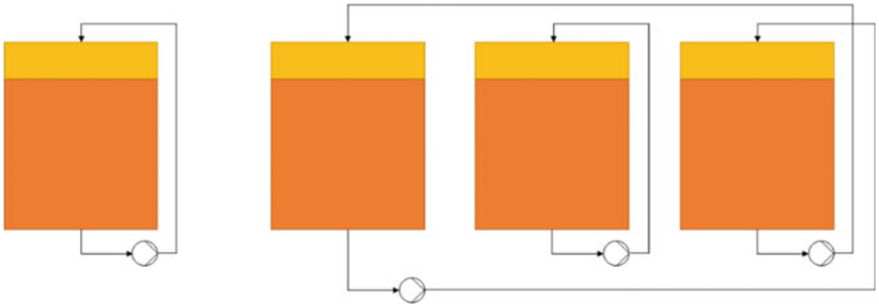

Fig. 3.2 Left: a single SBR reactor and Right: a multiple SBR reactor system

3.2.4.2 Continuous Process

In the continuous process, the substrate is fed constantly (continuously or in small batches with a defined interval of time), and as a direct consequence, the biogas production is almost stable.

The digesters can be vertical, horizontal, as well as in single or multiple stages. Depending on the type of mixing, they can also be further classified.

Plug flow

Thanks to the simplicity of the system and low investment costs, this system is normally adopted for farm liquid effluent. Concrete tanks, usually without mixing systems and possibly with internal baffles to differentiate the hydrolysis phase are used. In plug-flow systems where the solid content of the digestate would be lower than 10% TS, sedimentation of heavier parts and floatation of lighter parts might take place leading to heavy maintenance cost for emptying the digesters.

Continuous stirred tank reactor (CSTR)

This is the most common type of reactor operating under wet condition. This kind of reactor is suitable for the digestion of a high variety of substrates from agricultural waste to industrial waste or energy crops.

The reactor normally has a cylindrical shape with mixing system and it can be operated at different temperatures and OLRs (2–5 $kg_{VS}/m^3/d$, higher ORL have been used only with some special substrates and after continuous digestion tests) (Fig. 3.3).

The mixing technology used in these reactors is well known and it guarantees a high efficiency of VSs digestion compared with other systems. On the other hand, the investment costs for this kind of system is usually higher than the others.

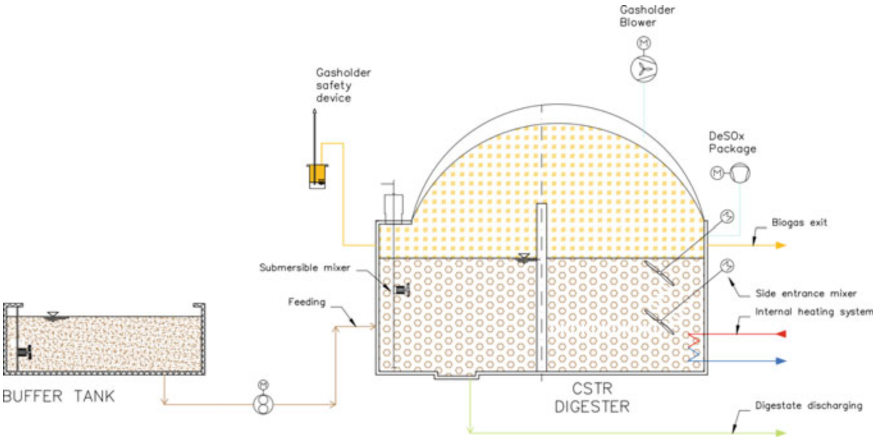

Fig. 3.3 CSTR basic schema [SEBIGAS s.r.l.]

High load reactor

Thanks to the retention of biomass and microbial population inside the reactor, this kind of process allows a higher efficiency and therefore, can operate at higher OLRs (8–20 kg_{VS}/m^3 d).

These systems are anyway not suitable for the digestion of substrates with high concentrations of particles i.e., total suspended solid (TSS) due to the tendency to accumulate the particles in the reactor.

The substrates usually treated are characterised by low level of TSS and high level of total dissolved solid (TDS) (such as industrial waste water, distillery waste, etc.).

The following types of reactor belong to this classification:

- Fixed or moving bed reactor
  The substrate and microbial population are attached to special supports (fixed or movable) installed in the reactor allowing the retention of the biomass while the substrate is recirculated to the supports to increase the contact time with the microbial biofilm.
- Upflow Anaerobic Sludge Blanket (UASB)
  In this system, a blanket of granular sludge is formed and kept in suspension in the tank. The combined action of the upward flow of the substrate and the gravity suspends the sludge blanket in the reactor (Fig. 3.4). This reactor is typically suited for wastewater digestion with low TSS.
- Membrane Reactor (MBR)
  This system uses a membrane to physically retain the biomass and microbial population inside the reactor while also separating the solid/liquid/gas phases. Thanks to its high separation capacity of and favourable performance in terms of achievable TSS, these reactors are particularly efficient for treating high pollutant content wastewaters.

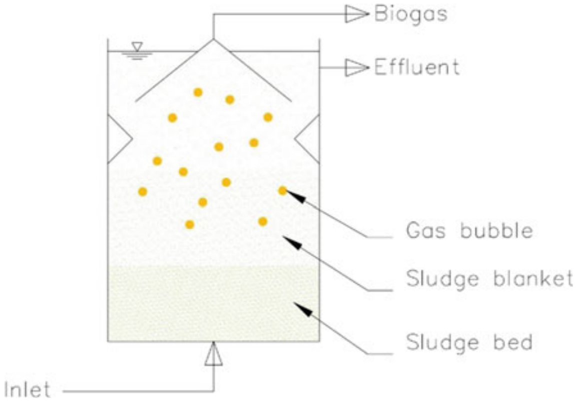

Fig. 3.4 A simplified schematic presentation of a UASB reactor

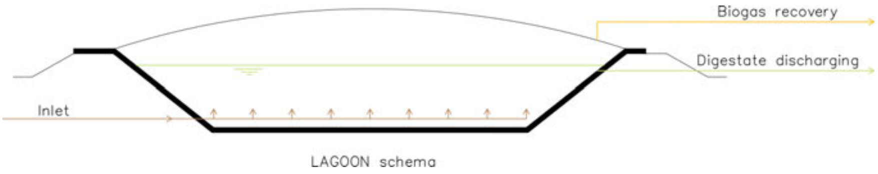

Fig. 3.5 Lagoon typical schema

Covered lagoon

This is the cheapest solution for anaerobic digestion process application (Fig. 3.5). It is a very simple and low investment cost application, but of course has some disadvantages like the high tendency for the formation of sedimented layers at the bottom of the system. This may necessitate emptying the system imposing high maintenance costs. Other disadvantages include huge area necessary, low efficiency due to non-controlled temperature of digestion, possible technical problems due to high volume of gas storage, leakage, etc.

The advantages of the system include possibility of designing a big volume system at a relatively low investment cost. This systems particularly of interest in case of very low TS/energy content substrates. Moreover, lagoons are easy to operate.

3.2.5 Solid Content Classification

Another type of classification for the digester technology is based on the solid content. Accordingly, the digestion process can be divided in two macro-group:

- Dry digestion
- Wet digestion

In wet digestion pumpable substrates are used while in dry digestion stackable substrates are used. In spite of that, there is no exact division line between these two types of digestion and it can just be assumed that wet digestion has an upper TS limit of around 10% while dry digestion has a lower TS limit of around 20%.

3.2.5.1 Dry Digestion

This process was initially used especially for the digestion of municipal solid waste (MSW) and organic fraction municipal solid waste (OFMSW), but it has also been used for energy crops digestion.

The advantages is that by having a high %TS inside a digester, the system could reach higher OLR values (even higher than 10 kgVS/m^3/d) which would consequently lead to smaller digestion volumes and lower investment costs. Moreover, there is no risk of sedimentation or floating layer formation as phase separation does not occur using a dry substrate.

To move dry materials, it is however necessary to have a strong system requiring much more maintenance and operation costs. It should also be highlighted that the absence of water implies a non-dilution of any possible inhibiting substances that may easily lead to a non-balanced system and acidogenesis phase prevalence.

3.2.5.2 Wet Digestion

Substrates like animal manure or wastewater/sludge do not need any additional liquid to reach the right TS% required by a wet system while for energy crops or other materials with TS% higher than 20–25%, it is mandatory to add water or to recirculate liquid digestate to keep the TS% at a right value in the digester allowing mixing and pumping of the substrate.

A typical configuration for wet digestion is CSTR digesters that need a good mixing technology to ensure an efficient contact between the microbial populations and the substrate.

The advantages are a smooth and economic operation giving stable production of biogas and simple usage of the plant.

The disadvantages include the possibility of the formation of sedimentation or floating layer (in case of non-optimised mixing design) which in extreme case may require emptying the digester. In some cases, it is also necessary to have a better pre-treatment system compared with dry digestion installations, but of course, the results would be higher efficiencies and higher specific gas production. An example is the OFMSW that needs a more accurate removal of plastics and sands before being introduced into a CSTR system, but the gas yield resulting from the process is higher than that of an average dry digestion system.

3.2.6 Process Design

After the selection of substrate to be used and the technology to be applied, it is possible to follow the main steps of biogas plant design as follows:

- Calculation of internal TS of the digester
- Recirculation or dilution
- Calculation of the volume necessary and selection of the type and dimension of the tanks

It is also important to keep in mind that every project has its own background and environment, and therefore, it is always important to study the local regulation regarding anaerobic digestion and in general, all construction regulations and permits that may affect the selection of the equipment.

3.2.6.1 Internal TS of Digester

The internal TS basically affects the mixing system (i.e., power and type of mixers or agitation system to be applied) and the possibility of sedimentation or phase separation.

In general, lower TS values are easier to mix, but phase separation, formation of floating layer and sedimentation are also more likely. On the contrary, higher TS values are more difficult to mix, but materials remain more homogeneous.

In some cases such as organic wastes, chicken manure, etc., it is essential to have a low TS at the entrance of the digester by allowing as much sedimentation as possible in the pre-treatment to avoid the introduction of large quantities of sands, shells and/or other undesired materials into the digester. In all other cases, the TS is a balance among TS′, and the recirculation and mixing system selected.

3.2.6.2 Recirculation or Dilution

To reach the selected target TS″ (TS inside the digester) the following steps should be followed (Fig. 3.6):

The quantity of added liquid to dilute (Q_D) at the beginning of the process (by recirculation or adding other liquids such as water, etc.) is calculated using the following formula (Eq. 3.8):

$$Q_D = Q' \cdot \frac{(TS' - TS'')}{(TS'' - TS_D)} \tag{3.8}$$

where:

Q_D	Quantity of liquid added for dilution
TS_D	Total solid concentration of the liquid added for dilution
Q'	Quantity of substrate fed into digester
TS'	Calculated TS concentration of the substrate after digestion
TS''	Target TS in digester

Therefore, the total quantity of liquid/solid fed into the digester (Q″) will be (Eq. 3.9):

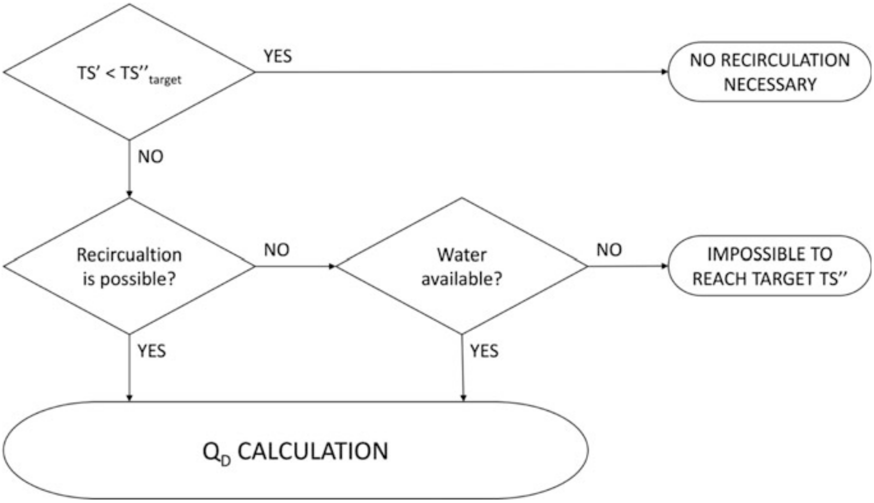

Fig. 3.6 Flow chart for the calculation of the recirculation or dilution

$$Q'' = Q' + Q_D \tag{3.9}$$

3.2.6.3 Calculation of Digestion Volume

The total digestion volume is defined by the HRT and OLR. Every substrate, depending on the digestion temperature and eventually on the pre-treatment applied, has its optimum retention time. Usually based on the findings of a batch test (that calculates the PGY), it is possible to predict the HRT of a given substrate.

OLR is estimated based on different biological parameters and represents the loading stress value of the digester, therefore, in general it is possible to force the OLR to higher values if the substrate is easy to digest by the microbial populations, while it should be kept at a lower level if the digestion process of recalcitrant substrates is intended.

Therefore, V_{HRT} [m^3] and V_{OLR} [m^3] can be computed as follows (Eqs. 3.10 and 3.11):

$$V_{HRT} = Q'' \cdot HRT \tag{3.10}$$

$$V_{OLR} = \frac{Q_{sub} \cdot 1000 \cdot TS \cdot VS}{OLR} \tag{3.11}$$

where:

V_{HRT} [m^3]	Net volume of digestion in accordance with target HRT
V_{OLR} [m^3]	Net volume of digestion in accordance with target OLR
Q'' [m^3/d]	Total daily volume fed into digester including eventual dilution
Q_{sub} [t/d]	Total quantity of substrate fed into digester daily
TS [%]	TS concentration of substrate
VS [%]	VS concentration of substrate
OLR [kg_{VS}/m^3d]	Target OLR for the considered substrate

The optimum total net digestion volume is the maximum value between the V_{HRT} and V_{OLR}.

In the design or construction phases of every and each biogas plant project, a big attention is focused on the investment costs. When the final selection on the digestion volume is made, the focus should not be only on maximising the biogas production or on the complete decomposition of the biomass, but rather efforts should be directed towards optimising the different parameters driving the Business Plan. It is sometimes possible to minimise the investment costs with a lower HRT and therefore, at the expense of lower specific biogas production and efficiency of the system, but this solution could be the only chance to have a feasible project.

From the environment point of view, the aim should always be to maximise the decomposition of the material to minimise the environment impacts of the digestate, but this also depends on the digestate usage.

3.2.6.4 Stages/Phases and Number of Digesters

The total volume necessary for the anaerobic digestion process can be divided in different tanks (or not) depending on the maximum dimension of 1 tank, the stirring capacity, the sedimentation expected, the number of stages desired, etc.

The complexity of the anaerobic digestion process lies in the fact that different phases exist throughout the process that may happen in sequence or simultaneously; each phase requiring its own optimal operating conditions such as temperature and pH.

Hydrolysis and acidogenesis are faster and they have higher efficiencies at low pH and high concentrations of substrate, while methanogenesis is inhibited by low pH values.

Inside a well-designed reactor, all four reactions can be taking place contributing to the overall anaerobic digestion process, there are for sure compromises though. Nevertheless, the concept of fully optimising every single step of digestion, necessitates separating different stages/phases of the process. Having more than one digester leads to other advantages as well such as:

- The calculated HRT is statistically more similar to the real one. The digester (e.g., CSTR) is continuously stirred and the materials inside should be approximately homogeneous, therefore, when a particle is extracted, its real retention time follows a normal distribution ("bell curve"), so there is a chance that a particle exits before or after the calculated HRT time.

  In case of an earlier exit, the digestion process could not be finished with a resulting lack of efficiency of the system and lower biogas production compared with the potential value, while if the particle exits later, there is almost no benefit.

  Based on this simple concept, it is clear that a double stage gives the possibility to mediate the normal distribution and reduce the standard deviation of the "bell curve".
- There is always a back-up. This means that in case of failure of one of the digesters, there is the possibility of using the other one to balance the process and the plant will not completely stop.

Single phase reactors have the all phases working at the same time in the same environment. This kind of design requires a lower OLRs (usually in the range of 1–4 kg_{VS}/m^3 d) in order to ensure a sufficiently high stability of the system.

Double phase reactors allow the optimisation of the four phases of digestion. In the first step, the best conditions for the hydrolysis and acidogenesis are usually achieved, i.e., a retention time of 1 to 5 d and OLR of >10 $kg_{VS}/m^3/d$ to increase the speed of the first 2 phases and avoid the start of the followings two.

The rest of the digestion takes place in the second step and the substrate is treated based on the design HRT.

Double stage reactors is a hybrid solution based on which the plant is designed with multiple digesters, but the system is not forced to have a clear separation of the digestion phases. In fact, all four phases happen together in different digesters, but in different percentages, so that the overall process is more stable and easier to operate even for non-skilled operators.

The choice of the configuration depends on the costs and benefits, and therefore it is always a good idea to discuss the different options and associated benefits during the preliminary design phase.

3.3 Plant Description and General Rules of Good Design

Once the biological and process parameters are established, it is then time to concentrate on the different areas forming a biogas plant. Biogas plants are usually non redundant systems as the investment costs target does not allow duplication of systems, equipment nor area of the plant. Due to this reason, it is more and more important to achieve an optimum design not only concerning the biological parameters such as HRT, OLR, and therefore net volume of digestion, but also it is decisive to have an overall harmonised design that avoid any problems in any areas.

Every step of the process from the receipt of material to the digestate usage and disposal could potentially be a bottle neck of the plant that may lead to stop of production.

A biogas plant can be divided into five main areas:

1. Substrate management area (receipt, storage, transportation to feeding, etc.)
2. Feeding and/or pre-treatment area
3. Anaerobic digestion area
4. Gas storage, treatment, and usage
5. Digestate storage/usage/disposal

The followings paragraphs aim at providing a general overview on the different areas explaining the possible choices and parameters that could influence the design.

3.3.1 Substrate Management Area

3.3.1.1 Substrate Receipt

It is important to keep into consideration the frequency, quantity, quality variation, and general variability of the material received to be prepared and ensure minimum possible energy loss prior to the biogas transformation.

Some substrates, like the energy crops in Europe, are usually received once per year, therefore, it is very important to be perfectly organised in the receipt, storage, and conservation technics choice so that the losses are minimised. In other countries, such as South East Asia or South America, there is a chance to have multiple harvests (2–6) per year for certain types of energy crops and this automatically influences the dimension of storage and the frequency of receipt. On the other side, energy crops collection in Europe is standardised and it is quite common to have very similar quality from one year to another, however, when harvesting more than once per year, the quality and characteristics of the materials are strongly influenced by the weather condition and seasonal changes and therefore, the variations in the substrate are less predictable, necessitating having a more flexible design.

A particular section could be dedicated to the wastes usually received 5 to 7 d a week (e.g., OFMSW or other industrial/food waste), but these wastes may produce reek and it is therefore suggested to receive them in a close building maintained slightly under pressure by using external blowers driving the air into odour control system (e.g., biofilters). The air recycle ratio changes in accordance with the local regulations, but as a general rules, it should be in the range of 2 to 4 air cycles/h (meaning that a building with an internal volume of 10,000 m^3 would need blowers with a capacity of 20–40,000 m^3/h to keep odour under control). It is usually suggested to keep separated the area where the operators stand or work continuously and the area where the operators visit just sometimes. In this way, it is possible to apply different air suction ratio to have 4 recycles/h in the working area and around 2 recycles/h for odour control.

Some other substrates like liquid or solid manure from animal farms do not even need any storage as they could be received on a daily base. In this case, the design should include a buffer area for the daily discharge and feeding into the plant.

3.3.1.2 Storage Area

The storage area is where the biomass to be used is stored for a certain period in accordance with the collection and receiving periods (which may vary from hours to 1 years).

The key point for a storage area are:

- To have enough volume to store the materials considering the flexibility and variation of characteristics of the materials to be used during the life of the plant.
- To keep the quality of the materials as much unchanged as possible to avoid loss of energy during storage period.

The storage structures in use are vertical silos or horizontal silos. Vertical silos are suitable for grains, cereals, or liquid products like oil or whey, while horizontal silos are more suitable for silage biomasses (grass silage, corn silage, energy crops silage, etc.). The horizontal silos could also be used to store agroindustry by-products or the other substrates to preserve their characteristics during the process.

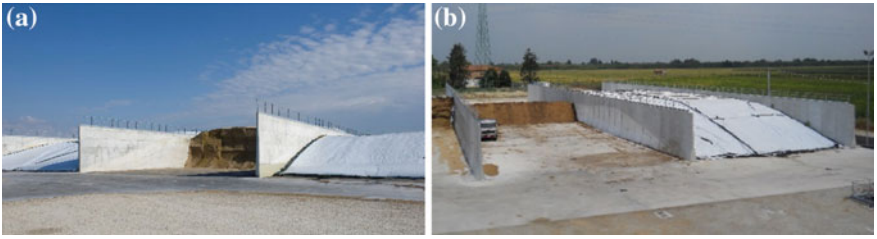

Fig. 3.7 Examples of horizontal silo storage, **a** constructed on site and **b** pre-casted silo storage [Sebigas a division of Exergy S.p.A.]

The horizontal silo storage systems in biogas plant can be constructed in full from concrete or compacted ground or a combination of both.

The concrete solution is probably more reliable with the highest durability, but it is also costly to build. The wall can be constructed on site or pre-casted (Fig. 3.7a and b, respectively), the pre-casted concrete is generally more durable and holds more favourable acid resistant characteristics and is therefore, recommended if available on the market. The durability of walls constructed on-site depends on factors such as skills of the construction company, weather conditions, and concrete mix quality.

The fully compacted ground solution is associated with a high permeability of the percolate (liquid coming from silage/stocking procedure) into the ground, and should therefore be avoided.

It should be noted that a certain amount of percolate is generally generated through the silage procedure and it is a good practice to collect and eventually use it in the digester or anyway discharged/treated in accordance with local environmental rules and regulations.

The silobag is another possible solution for material storage. It is a kind of big plastic bag with a good resistance against severe weather conditions and that help to preserve the materials during storage. The costs of the machinery necessary to fill and empty the bag should be taken into consideration.

The size of the storage area basically depends on two parameters:

The total quantity of biomass to be used in digestion ($\mathbf{Q_y}$): is the total expected quantity of biomasses introduced to the anaerobic process to produce the target energy per year. $\mathbf{Q_y}$ can be calculated using the following equation (Eq. 3.12):

$$Q_y = \frac{Q_{CH_4}}{PGY \cdot C_{CH_4} \cdot VS \cdot TS \cdot (1 - \mu)} \tag{3.12}$$

where:

PGY	Potential Gas Yield [Nm^3_{biogas}/t_{VS}]
Q_{CH_4}	Quantity of methane produced in one year [$Nm^3_{CH_4}/y$]
C_{CH_4}	Concentration of methane in the biogas [%CH_4]

TS	Initial TS concentration of the substrate [%]
VS	Volatile solids concentration referred to TS [$\%_{TS}$]
μ	Lost of VS during conservation process [%]

Duration of the availability (t_{sub}): is the duration in time the stored material is used in one year. Plants that use only energy crops with one harvest per year are forced to have a huge storage area to ensure sustainable material supply annually. On the contrary, plants that use multiple substrates and/or by-products with regular receipt are less subjected to the need for big storage areas.

Through these two parameters, it is possible to calculate the total volume of storage necessary (Eq. 3.13):

$$V_{storage} = \frac{Q_y}{\rho_{sub}} \cdot \frac{t_{sub}}{D_{365}} \cdot SF \tag{3.13}$$

where:

$V_{storage}$	Total volume of storage required [m^3]
Q_y	Yearly quantity of substrate used [t/y]
ρ_{sub}	Specific weight of the substrate silage [t/m^3]
t_{sub}	Duration of the availability [days]
D_{365}	Days of full production expected in one year [d/y]
SF	Safety factor

The loss during the storage may vary considerably depending on different factors ranging between 5 and 7% (minimum and non-avoidable) for a good silage up to 30–40% in cases of misapplication of good silage procedures.

The specific weight of the substrate may also vary remarkably depending on the following non-exhaustive variables:

- Size of harvested material (usually 5–15 mm is the suggested length)
- Moisture content
- Press force during silage operation
- Height of the storage

Concerning the total volume of the storage, a minimum safety factor (suggested as 10–15%) should be taken into account to compensate for unexpected delays in the receipt of the subsequent batches of the raw materials, possible variations in the characteristics of the materials during storage time, etc.

All materials stored in horizontal silos must be covered by plastic lining to prevent oxygen entrance that may lead to oxidation and VS losses.

The silo storage may have different configurations depending on the available area or the construction technics (Figs. 3.8 and 3.9):

- Single or multiple
- Closed or open

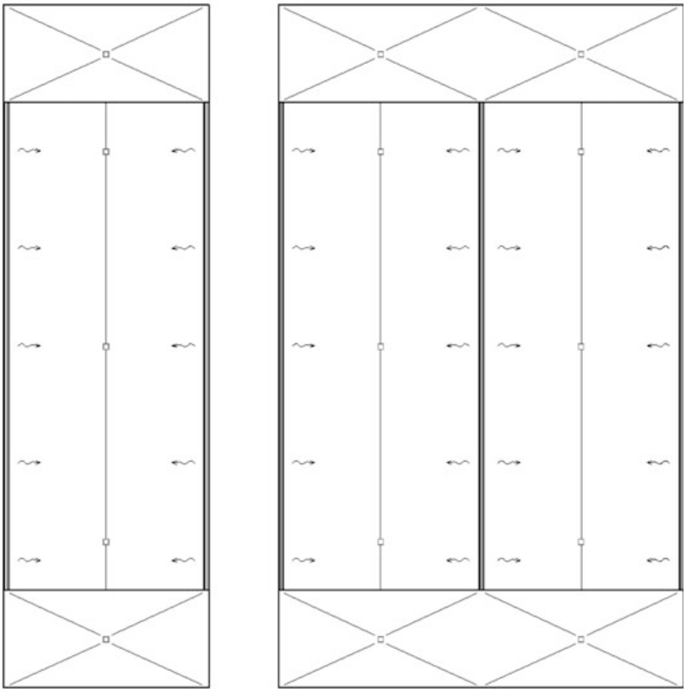

Fig. 3.8 Single silo storage (left) and multiple silo storage (right)

The width of each silo storage is designed to minimise the surface exposed to oxygen in the front. Moreover, the more the materials are pressed, the less the oxygen can penetrate through the surface.

As a general rule, it is suggested to have about 1 m of the front cut per day to minimise the exposure time of the front material and therefore, the loss of energy.

A silo storage with double side entrance allows a higher flexibility during plant operation as the "old" material that have been stored can be removed at first while the "new" materials can also be used thanks to the opposite access to the silo. This option allows a First in First out (FIFO) logic in the storage operation avoiding long time storage periods and consequent loss of energy. If a closed configuration is used, it is possible to increase the volume of the stocked material per square meter as the end wall allows the materials to be pressed without a slope, but it only allows a FILO strategy to be implemented.

A normal time limit for the silo storage is one year; two years is also possible but hardly suggestable.

Every silo storage releases percolate that could be posing pollution risks to soil and water resources. Therefore, it is strongly suggested to design a collection system and to send the percolate to the digestion process. It is also important not to underestimate the quantity of the percolate released in the early phase of the storage soon after silage operation.

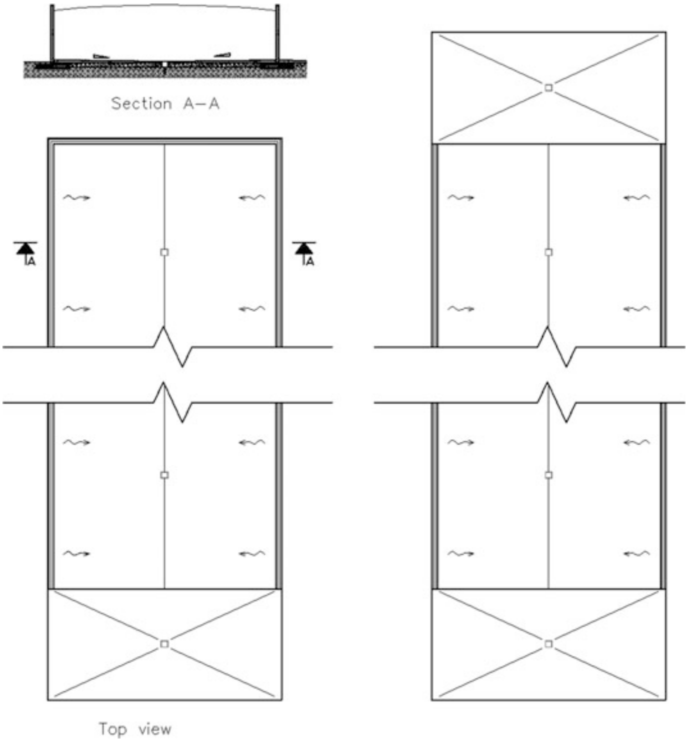

Fig. 3.9 A closed silo storage with one side entrance (left); an open silo storage with double side entrance (right)

The percolate usually has a very low pH, and therefore, it is important to take this information into consideration during the design of the civil construction to avoid any corrosion problems.

3.3.1.3 Transportation to the Feeding System

Wheel loaders are the most common transportation systems for the material from the storage area to the feeding system and has an average capacity of 2 tonne per trip. The distance between the silo storage and the feeding system is also a source of operational costs and should be considered.

Due to the obvious limited speed of the wheel loader, the longer the distance between the feeding system and farthest point of the storage, the more time-consuming the transportation and loading operation will be. The time needed by the operator to transfer the material from the storage to the feeding area should be calculated to prevent probable bottlenecks during plant operation.

Cranes are operated manually needing the presence of an operator during operation or are fully automatic transferring biomass from the storage area based on a predesigned route and algorithm. Cranes are a good solution when materials are received on a daily basis and are unloaded in a pit.

3.3.2 Feeding Equipment

The feeding system is the access door for the materials to the anaerobic digestion plant. There are various systems that can be applied to perform the same operation and of course there exist different prices and quality levels.

The feeding equipment is very important for the plant as there is no buffer nor spares in case of failures. It is preferable to design a biogas plant with at least two possible ways of feeding, a principal feeding system and a secondary system. The secondary feeding could also be a simpler and cheaper solution, but at least it would allow the operator to feed the plant in cases of maintenance of the principal system.

3.3.2.1 Liquid Feeding

Buffer tank

Also called receiving pit/tank, it is the tank used to collect and homogenise the pumpable substrate to be fed into the digesters. It is applicable as a primary feeding system for liquid manure, some vegetable waste, fruits, juice, etc.

In case of non-pumpable substrates (usually TS values over 10–12% depending on the substrate and the pump used), there is the possibility to dilute them in the buffer tank together with liquid fraction of digestate, water or digestate itself to have a pumpable, mixable, and homogeneous liquid. When the digestate is used, some gas is formed in the buffer tank which brings about some consequences:

- Gas forming and possible Atex classified area
- Loss of energy with linear relationship with time of contact between digestate and fresh material
- A higher quantity of recirculation has to be used to reach a favorable TS
- Not reducing the HRT as the digestate is just pumped outside for a while and pumped back.

While in case of using liquid fraction of digestate, the following consequences could be expected:

- Some bacteria are recirculated back to the fermentation and it may help the process
- It is effective on decreasing HRT

- Increasing inhibitory effects due to concentration of nitrogen, salts, and others contaminants
- Gas forming and possible Atex classified area.

In case of using water, the following points need to be considered:

- Higher cost of operation if water is not available for free
- Environmental impacts as the water used is mixed with the digestate and therefore, will then have to follow the same regulations
- Reduction of HRT (but less than using liquid fraction of digestate)
- Reduction of inhibitory effect.

The mixing system used in buffer tanks is very different from those used in digesters. The buffer tank usually receives materials in batch, in big quantities, and the scope is to homogenise the liquid and solids in a short time.

Near the charging point, a powerful mixer should be used to move away the biomass immediately after their introduction into the tank. The suction point of the pump from the buffer tank has to be kept clean to avoid any sedimentation blocking the suction pipe. Fast mixers are suitable for the application (see Sect. "3.3.3.4—Mechanical mixing system") and the installed power should be in the range of 30–70 W/m^3 depending on the characteristics of the materials to be homogenised.

The volume of the buffer tank should be calculated following the same considerations taken for the silo storage. It is important to consider the frequency of material received, the quantity of material, the total volume fed per day, the number of feeding cycle, and the availability of operator on site to follow the mixing and preparation activities.

A safety margin should also be considered when performing the volume calculations in provision of possible modifications in any of the mentioned criteria affecting the sizing of the tank. It is also suggested to have a minimum of 50 cm freeboard for open tanks and 20–30 cm freeboard for roof closed tanks.

Depending on the vehicle used to charge the tank, different constructions and dimension methods can be applied. In case the liquid is introduced with a slurry tank truck without discharging pumps, an underground solution would be suggested, while if there is the possibility to pump the liquid, an above-ground solution would be better allowing the installation of suction pumps to feed the digester at ground level, easing the empty procedure in case of maintenance.

When buffer tanks are used to mix and homogenise solid materials with the liquid fraction to create a pumpable solution, the level of the tank has to be calculated considering the maximum discharging height of the wheel loader/tipping trailer.

Direct feeding

The buffer tank can also be directly fed by pumps connected to the farm collection pit. In this case, it is recommended to include the function of the pumps and the instruments of the buffer tank in the PLC to check the level and to eventually stop pumps. Moreover, a remote control for start-stop could also be installed to ease the charging operation.

3.3.2.2 Solid Feeder

When solid biomass cannot be loaded in the buffer tank due to:

- Quantity
- TS (%)
- Missing recirculation
- Available space
- Operator availability
- Operator skill
- Atex area risk
- etc.

It is then possible to equip the plant with a dedicated solid feeder machine. There is a wide range of solid feeder types available on the market. These feeders can be classified according the following main characteristics:

1. Type of container and biomass transporting system
2. Wall and floor material
3. Type of injection system (injecting materials into the digester)

Other than the type of feeder, it is important to identify the volume necessary and the output capacity to fulfill the digester requirements in terms of daily volume/weight and in terms of frequency of the cycles.

Type of container biomass transporting system

Walking floor is composed of pushing elements (sliding beams) arranged in parallel (Fig. 3.10). This system is suitable for transportation of light materials with low bulk weight. This technology have been used in the trucks' floor with automatic discharging system as well. A hydraulic unit normally activates the movement of the sliding beams at the required speed and the material is transported by friction.

Push floor has different carriers, depending on the task. The carriers slide on steel rails directly positioned at the bottom of the floor (Fig. 3.11). The racks of the

Fig. 3.10 Walking floor system [Huning Anlagenbau GmbH & Co.KG]

Fig. 3.11 Example of push floor rack installed in concrete bunker with lining protection from corrosion [Huning Anlagenbau GmbH & Co. KG]

push floor are moved forward and backward by hydraulic cylinders positioned on the head or on the tail of the container depending on the discharging system adopted.

The material is transported in the direction of the exit.

Push-off system consists of a shorts side wall actuated by a hydraulic cylinder, the wall slides along the floor in the direction of the exit of the system so that the material is physically pushed forward (Figs. 3.12 and 3.13). This system is a flexible solution that allows to transport different kinds of material, in particular heavy material or non-chopped material that might be difficult to transport forward with other systems.

Chain system is typically used for manure distribution on field trucks. This system is seldom used for feeding application in biogas plants due to the high maintenance costs.

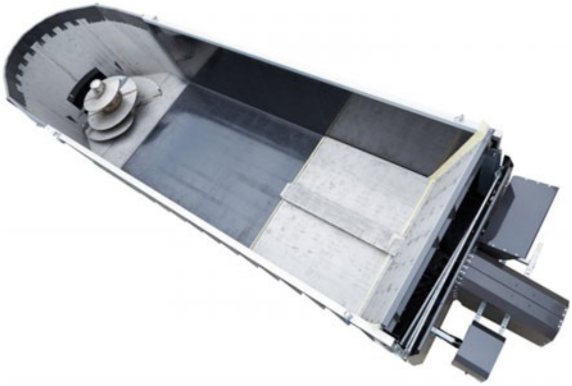

Fig. 3.12 A typical solution of push-off system [Fliegl Agrartechnik GmbH]

Fig. 3.13 The hydraulic cylinder and installation that moves the push-off wall [Fliegl Agrartechnik GmbH]

Horizontal screws is a method of transportation especially applied for big size biomass, often not chopped. A typical application is the slaughterhouse waste, animal carcass, etc.

Vertical mixing screws is based on the *Mixer-wagon* agricultural machinery normally used to mix the feeds for livestock and to distribute them along the feeding trough. The vertical mixing screws could be one or more (usually up to 3 maximum). This system has some disadvantages including have high electrical consumption (the screws need powerful motors), high maintenance (every screw is equipped with a gear reducer under the container or a bevel gear reducer just outside), and high wearing (the material is mixed continuously while transported towards the exit). One of the biggest advantages is that it is possible to load it with different layers of substrate while always having a homogeneous outcome material leading to a stable production with a well-balanced specific yield per ton of material. Given the high variations in the substrate used in biogas plants, if the material fed into the digesters is not homogenised, there might be fluctuations in gas production during the day (Fig. 3.14).

Fig. 3.14 The installation of a vertical mixing screws solid feeder (left) [Sebigas a division of Exergy S.p.A.] and a single vertical screw feeding system (right) [Trioliet B.V.]

Direct solid feeding is a very simple system used in cheap construction configuration for underground digesters (“round lagoon”). The system uses an opening on the side of the digester, under the gas holder, to create an opening wide enough to have the possibility to push the material inside the digester by means of a wheel loader. The system allows to have a very low construction costs, but may lead to higher operation costs as it is sometimes necessary to have an additional external mixing system operated by a tractor to mix the material at the entrance of the digester.

Wall and floor material

Different types of materials are used for the construction of solid feeders. The biomass container can be made of stainless steel, wood (Fig. 3.15), high density polyethylene (HDPE) (Fig. 3.17), carbon steel (with or without protection) (Fig. 3.16), concrete, etc.

It is important to plan the real lifetime usage of the plant to identify the correct materials suiting the duration the plant is supposed to be in use. The choice is made with reference to biomass characteristics:

- pH or corrosion action
- Wearing capability
- Liquid content and percolate

The costs is of course a key factor influencing the final choice.

Type of injection system (injecting materials into the digester)

After selection of the container, internal transportation system and their respective construction materials, it is time to analyse the advantages and disadvantages of the available solutions for the injection system—that is, the way to bring the material inside the digester.

Fig. 3.15 Wood wall solid feeder installed on Sebigas a division of Exergy S.p.A. plant

Fig. 3.16 Special polyethylene coating to protect the carbon steel frame [Trioliet B.V.]

Fig. 3.17 Feeding system with HDPE wall to prevent corrosion [Fliegl Agrartechnik GmbH]

The following principal injection systems are briefly described:

Screw conveyors are the most common injection system used in connection to solid feeders (Figs. 3.18 and 3.19). The conveyors can be classified based on screw diameter, pitch, type of pitch (constant or variable), thickness, construction material, internal guiding shaft, external protection, etc. These screws can be easily inclined and used in different situations. Being a closed system, it has the advantages of preventing powder losses and limiting unpleasant smell, yet it is costly and especially due to wearing of materials, it may need a high maintenance cost.

Belt conveyors are also quite common in European constructions. They allow the transportation of non-homogeneous materials and can not be easily blocked due to the absence of small gaps in the system. They also allow speed adjustment without facing rotation speed problems. The system also suffer from some disadvantages like high wearing and maintenance costs due to the high number of rollers and bearings, and limited inclination potential to avoid sliding back of the transported materials. The best application of this system is for waste transportation rather than energy crops.

Fig. 3.18 Combination of horizontal, vertical, and inclined screw conveyors to transport the material from a solid feeder to a digester

Fig. 3.19 Example of an inclined screw conveyor to transport the materials from a solid feeder to a digester [Sebigas a division of Exergy S.p.A.]

Solid-liquid pumps include a solid and liquid mixing buffer/box prior to the pumping body. Both lobe and screw pump are available for this solution. The advantages are a pre-mix of the substrate with the liquid (usually the digestate directly taken from the digesters), bearing a lower mixing electrical consumption to homogenise the materials, possibility of swift maintenance, and the possibility to install it far from the digester. It should be mentioned that the last item could also be unfavourable as it increases the cost of installation of the pipes and leads to pressure loss. The disadvantages of this system include, more complex piping system, as well as more complex software to control the liquid recirculation and liquid level inside the pump. Figures 3.20 and 3.21 presents example of solid-liquid pumps.

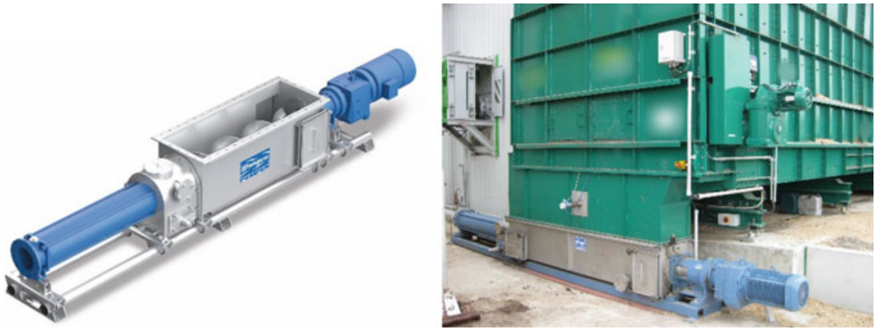

Fig. 3.20 Example of a solid-liquid pump located after the mixing box to send the materials into the digester [Pumpenfabrik Wangen GmbH]

Fig. 3.21 Example of a solid-liquid pump in combination with a grinder [Vogelsang Italia S.r.l.]

3.3.3 Anaerobic Digestion Area

This area of the plant is the core of the system and, even if apparently simple, includes small design details that may lead to successful or failed designs and operations.

Each digester has a volume ranging between 1.000 and 8.000 m^3 or more. Whenever it is necessary to empty such a volume, it takes a long time and the digestate has to be also temporarily stored in another tank. This operation may not be possible or may require additional costs for digestate disposal. For these reasons, it is important to have a reliable design incorporating different critical parts efficiently to maximise the availability of the plant allowing to reach the operation hours targeted in the original business plan.

3.3.3.1 Tank Construction

Digester tanks are made of reinforced concrete, carbon steel, stainless steel, or special coated steel. A digester, to keep an anaerobic process running inside, must be gas tight over liquid level and liquid tight under liquid level.

In any cases, it is important to carefully consider the underground condition and to perform a good geotechnical survey as well. This investigation is often underestimated (especially in some countries), yet there is a good chance to choose a more economical solution for the construction of the tank if the full data necessary for the geotechnical design and soil bearing capacity calculations are available.

In some cases, to bear the load of the digester and its liquid content, it is enough consolidate the ground or to stabilise it with stones and gravels, while in the majority of situations, it is necessary to implement more severe solutions such as piling, jet grouting, underground starting level, etc.

Reinforced concrete can be made on site by using a rebar beam cage or by using a special formwork without a reinforcing steel, allowing the structure to have a higher tensile strength (Fig. 3.22). There is also the possibility to install pre-casted panels and assemble them on site. Concrete constructions present considerable advantages in terms of flexibility in shape and dimension, possibility to be modified during construction in case of any modifications in the original design, capable of withstanding high loads, and being usually cheaper than other types of installation especially in large diameters. On the other side, highly skilled construction companies are required to ensure that the structure is liquid- and gas-tight. Strict tests are crucial carefully investigating the tanks as they must last for at least 15 or 20 years under severe environmental conditions. In case of wrong construction quality, it is important to take counter measures as soon as possible. During the operation, leaking of the digestate may affect the durability of the rebar embedded in the concrete due to action of liquid and oxygen, while in the top portion of the digester, possible gas leakage may lead to early corrosion due to acid gas (H_2S and moisture). Usage of high-grade concrete, right mix of additive, and professional

Fig. 3.22 Concrete casted digester during construction

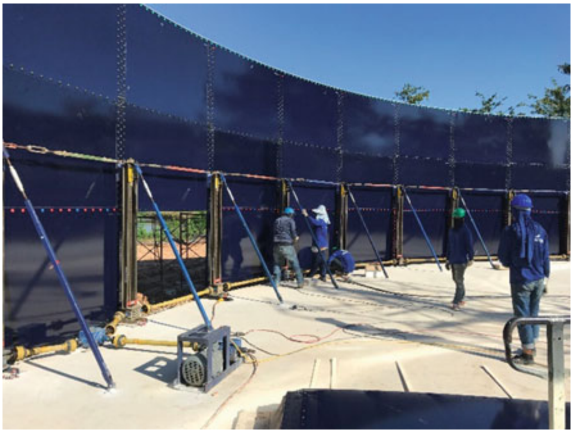

Fig. 3.23 Glass fused tank under installation

planning of the pouring are mandatory for successful construction of reinforced concrete. The cement construction is cheaper compared with other installation, but it should be kept in mind that repairing costs could be exponentially higher as well.

Steel digesters are installed directly on the concrete basement, which is a key point for the tightness of the tank (Fig. 3.23). The parts of the tanks are usually connected with bolts followed by a cement pouring while a sealant on top seals the connection. The construction methodology can be very different: from welded metal sheet to bolted panels depending on corrosion and wearing effects. Usually V4A steel is suitable for H_2S contact, but with high concentration of oxygen and moisture, corrosion may become severe anyway. Coated panels (like glass fused or similar applications) are more resistant to the corrosion effect. Usually steel tank cannot be positioned underground as they have a very good resistance to the inside pressure (the pressure imposed by digestate on the wall), but have little resistance to the outside one (the pressure imposed by compacted ground on the outside wall of an empty tank). In case of underground solutions, the bottom rows of panels have to be oversized to resist to the pressure.

3.3.3.2 Tank Protection

The protection of the wall or roof of the digesters is very important to increase the durability of the structure during the lifetime of the project. Above the liquid level, concrete tanks can be coated with special PE membrane. The best option is to pour the membrane directly with the concrete so that no gas can penetrate between the protection membrane and wall causing corrosion (Fig. 3.24).

Special epoxy painting has been developed recently to protect the concrete and has been found promising especially in case of non-wearing material. In case of wearing material, there could be the need to open the digester after a certain time (years usually) to restore the original situation.

Fig. 3.24 PE membrane protection installed during pouring of the concrete to protect the surface above liquid level

3.3.3.3 Shape and Dimension

The selected net volume of digestion for each tank can be achieved through different shapes and dimensions. The main parameters are diameter, height, freeboard, thickness of the wall, bottom plate shape, and number of columns (if any).

Each parameter is driven by a mix of technical solutions and decisions. The diameter is related to the mixing system adopted and the substrate in the digestion. Lowering the ratio between the height and the diameter of digesters over 0.5–0.6 usually helps with the stratification and therefore, sedimentation and extraction from the bottom, but can lead to stratification of the digestate. Small diameter digesters are also easier to be mixed as the thrust of the mixer and distance of agitation can reach the middle of the tank. In flat digesters (the ratio between height and diameter in the range of 0.25–0.40), stratification (by energy crops, grass, etc.) could be avoided, but not all the surface is easily mixed and so it is probable to have areas with higher sedimentation.

A high digester also presents technical limitations for the installation of mixers, for example with heights over 10 m, the submersible mixer is not usually installed properly due to the length of the guiding shaft and the difficulty with lifting and lowering the mixer. Over 15 m, bottom lateral entrance mixers may face problems related to the sealing and tightness and special versions should be selected due to the pressure of the digestate. Vertical mixers installed at the centre of the tank should have longer shafts without guide at the bottom and therefore, they present the risk of high vibration and oscillation of the shaft.

The freeboard selection is mainly related to the position of the gas exit and the material used in digestion. The side exit of gas may reduce the possible freeboard as the bottom level of gas exit pipe should be at least 20–30 cm higher than the liquid level to prevent it from going into the gas line. In case when foam formation is expected, a higher safety factor should be applied and it is suggested to consider the bottom level of gas exit pipe at least 70 cm higher than the liquid surface.

The bottom plate can be flat or conical. The conical construction is not easy to build as it is necessary to utilise special tools during pouring. Conical shape allows the extraction of sedimentation through a pipe positioned at the centre of the cone. The flat surface is much easier to build and it can be cleaned by a submersible mixer with proper orientation and level adjustment. Usually conical-shaped digesters are used only for municipal solid waste or sometimes for poultry manure digestion.

In digesters with gas holders, it is usually necessary to have a central column that can be built in reinforced concrete, special wood or stainless steel. Reinforced concrete solution needs a special formwork, but it is a reliable solution while wood is a solution definitively affected by the quality of the available wood and is generally not recommended considering the installation environment. Stainless steel can be utilised, but as described, it is necessary to carefully control that no oxygen is present in the tank as it might affect the duration of the steel.

In case of digesters with roof, the presence of column depends on the diameter and design. It is normally enough to have one central column to bear the load of the roof, but also multiple column solutions can be adopted to decrease the thickness (and costs) of the roof as far as it provides the possibility to install an agitator at the centre of the tank.

3.3.3.4 Mechanical Mixing System

The mixing system is a key factor in CSTR technology as it results in the homogeneity of digestate inside the tank, but also accounts for the largest electrical self-consumption proportion. There is no exact formula to calculate the necessary characteristics of mixers. They can be classified based on speed, power, type, and installation.

- Speed: fast (shearing effect), slow (kneading effect)
- Power: expressed in kW
- Model: submersible motor, external motor
- Installation: vertical, horizontal, inclined, adjustable, fixed

The TS content and viscosity are the factors that drive the choice between the fast or slow mixing system, nevertheless, a combination of various systems is a common practice to enjoy the benefits of both systems. The agitator can operate continuously or intermittently with stirring interval that has to be set-up case by case based on the practice and experience during the operation of the plant. In the first period after start-up, it is usually a common practice to have longer and prolonged intervals of stirring times, while only after a certain period of stabilisation of the plant, it is possible to optimise the electrical self-consumption.

Submersible motor mixers are often used for waste water treatment applications and the design has been adapted for biogas applications. The motor can be

Fig. 3.25 Submersible mixer installed in concrete tank digester

either electrical or hydraulic, with gear reduction or with speed adjustment through motor winding design. The housing of the motor should be tight, as well as the electrical cable, with special attention to the gas side passage. The cooling of the motor is performed by the stirred liquid itself, therefore, in case of a wrong design, it is easy to reach a loop effect that could immediately lead to motor stop. If the mixer is too fast for the viscosity of the material and does not create enough flow through to cool down the motor housing, the motor temperature rises leading to over temperature stops. A slow or fast propeller can be installed to better adapt to the fluid characteristics. This kind of mixers are usually adjustable in level inside the tank which brings the big advantages of changing position, inclination and direction in accordance with the need of the plant. It is also easy to create a turbulent flow, break the scum (if formed) or floating layer as well as sediment material. Nevertheless, cavitation is possible, there are also a lot of moving parts and equipment inside the tank that may lead to difficult or frequent maintenance need, the motor may need be often extracted depending on the stirring time and interval. The extraction and replacement can be done through a special opening on the roof or gas holder, or a portion of the gas holder need to be opened. The guiding shaft is normally fixed at the wall of the digester so the mixer area of influence is the volume near the wall and the mixer effect cannot reach the centre of the tank (Fig. 3.25).

Different kinds of opening for maintenance are available on the market with different kinds of gas tightness systems. The best situation is to have an opening that could avoid gas exit during opening thanks to hydraulic sealing system (Fig. 3.26).

External motor agitators are characterised by a long through shaft that allows rotation transmission from the motor located outside to propeller located inside the digester (Fig. 3.27). Also in this configuration, slow speed or fast speed propeller can be installed to optimise the stirring of the fluid. In case of side entrance shaft

Fig. 3.26 Mixer dome for easy and safe maintenance of submersible mixer in gas tight tanks

Fig. 3.27 Inclined mixer with external motor during installation [Sebigas UAC Co., Ltd.]

and depending on the length, it is possible to install an additional support inside the tank to guide the shaft. In this case, special attention should be given to the choice of material and maintenance interval of the support, since it is necessary to empty the tank for maintenance purpose. The combination of external motor and slow speed propeller is quite common and gives the advantage of few moving parts inside the digester, possibility of continuous operation due to low electrical consumption, and prevention of scum formation. The area affected by the thrust and flow is much higher and allows a better homogenisation of the internal fluids.

In case of digesters with roof, it is possible to install a vertical shaft mixer positioned in the centre of the tank or anywhere near the centre of the tank (Fig. 3.28) (which is usually a badly mixed area) along with side entrance or submersible mixers. The flow direction is downwards below the mixer and upwards near the wall leading to bottom cleaning effect.

Fig. 3.28 Vertical shaft slow speed agitator installed at the centre of the digester roof [Stamo Maskin AB]

3.3.3.5 Access

During the design, it is normally suggested to keep an opening in the digester for future maintenance. In case of concrete or metal roof digesters, it is suggested to have a big opening to allow an easier passage of tools or machine in the digester for cleaning or emptying procedures. When a gas holder is installed on the roof, it is then enough to have a small passage to ease the entrance and exit of manpower during construction and installation phases.

3.3.3.6 Digestate—Sludge Transportation and Removal

Sludge and digestate are usually pumpable, and therefore, pumps driven by electrical motors are the most common solution for this purpose. Different parameters have to be considered for the pump selection:

- TS content
- Viscosity
- Need of specific flow not related to pressure drop

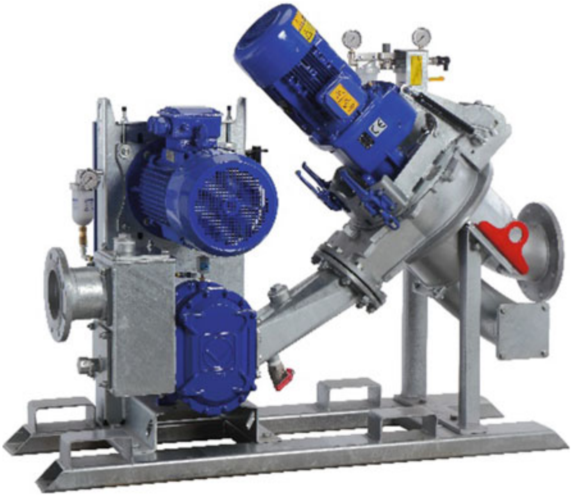

Fig. 3.29 Lobe pump in a special construction, directly connected to a grinder on the suction side [Vogelsang Italia S.r.l.]

- Installation position
- Maintenance need
- Pumps head
- Fluid temperature
- Running time
- Frequency of start and stop

Centrifugal pumps or positive displacement pumps like lobe (Fig. 3.29) or screw pumps are commonly used for digestate and sludge transportation.

Centrifugal pumps are suitable for low TS, low viscosity, variable flows in accordance with pressure loss and different temperatures. The advantages are the possibility to be installed either inside or outside the tank (submersible or external pumps), but this kind of pump is usually not the best choice for high head demanding.

Positive displacement pumps are volumetric pumps and the volume transported through each rotation and therefore, during each minute at a certain speed of rotation is always the same. Due to this reason, its application is particularly recommended when pumped volume needs be counted without instrument and of course with scant precision.

3.3.3.7 Heating System

As mentioned, the stability of the process temperature is a key factor to high efficiency. The environmental conditions affect both the entrance temperature of the biomass and the loss of temperature of the digestate in the tank.

To keep a stable process temperature, it is necessary to have a heating system controlled by the plant software. There are two possible ways to provide heat to the digestate: through internal pipes system or with external heat exchanger.

The internal pipe system is the cheapest solution both from investment and operational cost points of view. Two or more pipes are installed on the internal wall of the digester, in the bottom area. The hot water flow is forced to pass inside the circuit exchanging heat with the digestate around the pipes, the warmed digestate creates a convection flow keeping a homogeneous temperature in the digester. The application has to be installed in the presence of a good mixing system in order to prevent the formation of different temperature layers that may hinder the anaerobic digestion process.

In order of increase the efficiency, PVC, stainless steel rigid or stainless steel corrugated pipes can be used. The PVC pipes are cheaper, but need more rounds to have a good thermal exchange which could be an advantage in case of damage to one of the pipes. The stainless steel rigid or corrugated pipes are similar in terms of the corrosion and wearing points of view, but the corrugated pipe has of course a larger surface per linear length of the pipe which allows for a shorter line. Due to the corrugated surface, the corrugated pipes have a better heat conductivity and require a turbulent flow at lower speeds (consequently a lower flow is necessary from the recirculation pumps).

The external heat exchanger gives the absolute advantages of being cleanable and accessible for maintenance. The disadvantage is that it is necessary to recirculate the digestate in the heat exchanger while the hot water recirculation is also necessary. This increases the electrical self-consumption of the plant and it is therefore suggested in case of substrates that may lead to soiling effect or gluing effect on the surface of internal pipes or with high presence of sands that may have an early wearing effect.

A good solution to preserve heat and avoid temperature difference in the wall of the digester is to have insulated tanks. This is almost essential in thermophilic processes and highly suggested for mesophilic processes as well. The insulation can be done with different commercial material based on the application (Rockwool, high density closed cell extruded polystyrene, etc.).

The insulation should be protected from weather; corrugated steel plate can be installed for this purpose.

The thermal power needed for heat exchanger should be produced on site by the cogeneration system or by additional dedicated boilers.

3.3.4 Gas Handling

The biogas produced in the digester has to be used for the project purpose with a flow as stable as possible. To maximise the efficiency, reliability, and availability of the plant, the gas line should be designed to act as a buffering system to avoid stops.

3.3.4.1 Gas Storage

The biogas production also fluctuates in a certain range and to compensate for such fluctuations, a gas storage is usually planned.

In case of digesters with roof, the biogas is sent to an external or additional buffer storage. In case of gasholder mounted on top of the digester, the biogas produced is automatically stored.

The gasholder can be double or single membrane: single membrane means that there is only one membrane that store the gas dividing biogas from the atmosphere; while double membranes have an external membrane kept fully inflate by an air blower plus an internal membrane that can act like a real buffer for the gas storage passing from fully empty to fully inflated.

The material of the gas holder membrane can be either double-sided PVC-coated fiber fabric which are usually UV, microbial, abrasion, and biogas resistant; HDPE or ethylene propylene diene monomer (EPDM) rubber.

EPDM gas holders are elastic and therefore, characterised by a higher permeability; their duration is also affected by weather, especially by UV and therefore, are not considered as the best option. Breakage or leakage of this kind of membrane is frequent causing obvious loss of gas/money, but more importantly, leading to a high environmental impact that should be avoided especially in renewable energy production sites.

HDPE is a very common material, easy to weld and with a good permeability resistance. It is often used for lagoon constructions. It is cheaper, easier to weld on site and resistant over time. The limitation of HDPE is that it is not strong enough to be used at "high" pressures (not higher than 2-3 mbar usually).

PCV-coated fabric is the most common material for double membrane gas holder owing to its high resistance to permeability, strength, and duration over time (Fig. 3.30). PVC fabric is characterised by strength of the fabric and weight per square meter. The selection of the textile should be in accordance with the biogas pressure estimated in the design and presence of special shapes (balcony, etc.) that may increase the tension of the membrane in their proximity. The achievable pressure in PVC gas holder is in the range of 3–20 mbar. If there are no special needs, it is suggested to keep a lower pressure of the gas to prevent tension to the

Fig. 3.30 Example of PVC-coated fabric gasholder installed

textile and to increase the lifespan of the gas holder. Under the internal membrane, a net and belts system is installed to bear the load of the membrane when empty (belts) and to prevent the membrane to drop into the digestate (net). The net can also be used as a media for the growth of desulphurising bacteria.

The level of the internal membrane can be measured to provide a visual estimation or a signal to the PLC regarding the quantity of the gas stored in the membrane. There are many different systems by different commercial suppliers, from radar to water pressure based systems. If the level of the gas holder is one of the parameters used to control the engine power and start/stop, the measurement of the gas holder level should be quite precise and reliable.

The colour is also affecting the operation of the gas holder; a dark colour absorbs more UV and sunlight and therefore, its durability may be reduced. For the same reason, dark coloured membranes are subject to pressure variations in response to variations in weather conditions.

Finally, every storage system should be equipped with safety valves for over pressure and under pressure that release the gas in case of complete failure of normal operation.

3.3.4.2 Gas Usage

The biogas can be used for three main different purposes:

- Electrical and thermal power production (Cogeneration system)
- Thermal power production (Boiler)
- Biomethane production (Upgrading)

The most commonly installed system is the Cogeneration as it is a well-known system already used for electrical power production from natural gas and with a good after sales service worldwide. There are different suppliers for this kind of engine (Fig. 3.31). In the selection, it is important to check H_2S resistance, %CH_4 accepted, efficiency, cost of maintenance including overall maintenance (usually around 60,000 h of operation), and availability of spare parts and fast emergency service.

The boiler is usually a simpler system and it is normally important to check the resistance to H_2S.

The upgrading systems are different from each other and a specific analysis considering the required outcome, the input variability and characteristics of biogas, the cost of operation and maintenance, and long terms reliability of the supplier should be performed.

Fig. 3.31 MTU biogas engine installed in power-house solution [MSM Energy Solutions Co., Ltd.]

3.3.4.3 Gas Treatment

Every biogas using system (upgrading, cogeneration unit or boiler) has a minimum required quality of biogas in terms of pressure, CH_4 content, H_2S content, moisture, O_2, and others contaminants. There are different systems to meet biogas quality requirements: water scrubber, activated carbon, biological treatment, etc.

Every situation requires a dedicated study and selection of the system (if required). There are a lot of commercial products that can meet the requirements of every project and different systems can be combined to achieve a better result. For biogas engine, the minimum requirement is usually a chiller to remove the moisture (with dew point in accordance to the minimum ambient temperature) and a gas blower to increase the pressure.

3.3.5 Digestate Area

At the end of the process, the digestate should be extracted by the last digester. The quantity of digestate can be calculated through the following mass balance equation (Eq. 3.14).

$$Q_{dig} = \Sigma Q_{subi} - Q_{subi} \cdot TS_i \cdot VS_i \cdot PGY_i \cdot \rho_{biogas} \tag{3.14}$$

where:

Q_{dig}	Daily quantity of digestate produced [t/d]
Q_{sub}	Daily quantity of substrate in input [t/d]
TS	Initial TS concentration of the substrate [%]
VS	Volatile solids concentration [$\%_{TS}$]
PGY	Potential Gas Yield [Nm^3_{biogas}/t_{VS}]
ρ_{biogas}	Specific weight of the biogas [t/Nm^3]

3.3.5.1 Solid/Liquid Separation

The digestate coming out from the digesters may still have a high TS concentration. Under certain circumstances, it could be economically and technologically viable to install a solid/liquid separation system. The horizontal or vertical screw press is the most commonly used. The digestate is pumped into the separation system and it allows the liquid passing through the screen while the solid goes out from the front or top of the machine.

The efficiency of this type of equipment highly depends on the quality of the material: viscosity, size of particle, content of fibres, TS concentration, etc.

A solid/liquid separation system usually allows to remove 1–3% of the digestate TS from the liquid fraction while producing a solid fraction with 20–25% TS concentration.

Based on the TS assumption, it is possible to estimate the quantity of liquid and solid fractions.

$$Qs = \mathrm{Qdig}\frac{TS' - TSL}{TSS - TSL} \tag{3.15}$$

$$QL = Qdig - Qs \tag{3.16}$$

where:

Q_S Quantity of solid fraction
Q_L Quantity of liquid fraction
TS_S TS concentration in the solid fraction
TS_L TS concentration in the liquid fraction

Belt-type filter presses, centrifuges and worm separation are other solid/liquid separation systems used in biogas plants.

The separation of the digestate would be advantageous leading to:

- Reduced liquid quantity and final storage volume
- Have a portion of stackable product
- Reduced floating layer and solidification of surface in the final tank

3.3.5.2 Digestate Storage

The digestate produced is usually stored in final tanks with cylindrical or rectangular shapes. These tanks can be equipped with mixers so that the liquid can be homogenised before discharging. The agitator can be permanently installed, removable or tractor-tow driven.

Following the local regulations about odour control and nitrogen loss, the final storage tanks can be covered with gas-tight membranes or simply with odour control membranes.

The choice of gas tight cover is subjected to discussion in relation to the feedstock used, HRT, OLR, and resulting efficiency of the designed process.

A high efficiency plant usually releases a digestate with less than 2–3% remaining biogas potential, therefore, under non-anaerobic conditions and lower temperature of the final storage environment, it is difficult to have big loss in atmosphere. The gas tight solution is usually non-viable.

The dimension of the storage is defined primarily by the frequency of emptying the tank. This interval may vary from a couple of days to months (usually 180 d in Europe). The rainfall expected during such period of time should be added to the storage volume to prevent early full state of the tank.

3.3.5.3 Digestate Treatment

According to the local regulations, the digestate derived from certain feedstock cannot be spread on the field (example: slaughterhouse waste, household waste, OFMSW, restaurant waste, some industrial waste, etc.). Under such circumstances, an additional WWT should be added to remove N, salt, TS content and the other contaminants until reaching the quality required for sewerage or river discharge.

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