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Brief Description	The current document contains the technical description, design methodology and drawings of the (i) anaerobic treatment of a domestic wastewater in an UASB reactor and (ii) the process of biogas upgrade to methane.
Keywords	Anaerobic treatment; Domestic wastewater; UASB; Biogas valorization; Biogas upgrade

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EXECUTIVE SUMMARY

An integrated upflow anaerobic sludge blanket - constructed wetland (UASB-CW) system will be demonstrated in the HYDRO1 site of the HYDROUSA project. This demo site will treat the domestic wastewater of Antissa wastewater treatment plant (WWTP) located at the island of Lesvos, Greece.

The current document contains the design tasks of the activities of T3.1 (*Anaerobic wastewater treatment and biogas upgrade at community level*). Hence, it provides the technical description and design methodology carried out to develop the anaerobic treatment in the UASB reactor and the upgrade of the biogas generated.

The anaerobic treatment takes place in an UASB reactor, triggering the production of biogas and a certain amount of sludge. The biogas will pass through a filter of activated carbon to remove the hydrogen sulfide and then it will be upgraded to remove the CO_2 and convert it in methane, which could be subsequently used as a fuel in a vehicle used for dissemination of the project.

Therefore, this deliverable comprises a detailed description of all the equipment involved in the anaerobic wastewater treatment and the detailed design methodology of the UASB reactor and upgrading system. Furthermore, a preliminary description of the operation of the systems and the safety instructions which must be followed in the installation are included.

ABBREVIATIONS

BOD	Biochemical Oxygen Demand
BTF	Biotrickling Filter
CHP	Combined Heat and Power
CH_4	Methane
CNG	Compressed Natural Gas
COD	Chemical Oxygen Demand
CO_2	Carbon Dioxide
CW	Constructed Wetland
DEA	Diethanolamine
DIPA	Di-2-propanolamine
GPDC	Generalized pressure drop correlation
LNG	Liquefied natural gas
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
GLS	Gas Liquid Solid
HRT	Hydraulic Retention Time
H_2S	Hydrogen sulphide
OLR	Organic Loading Rate
PP	Polypropylene
PPD	Personal Protective Devices
PSA	Pressure Swing Adsorption
SRT	Solids Retention Time
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

An anaerobic biological process has been proposed in the HYDROUSA project for the treatment of the domestic wastewater. The anaerobic treatment process consists of the degradation of organic matter by anaerobic microorganisms, in absence of air (oxygen), leading to a considerable biogas production and a relative low sludge production (Figure 1.1, Henze et al., 2008).
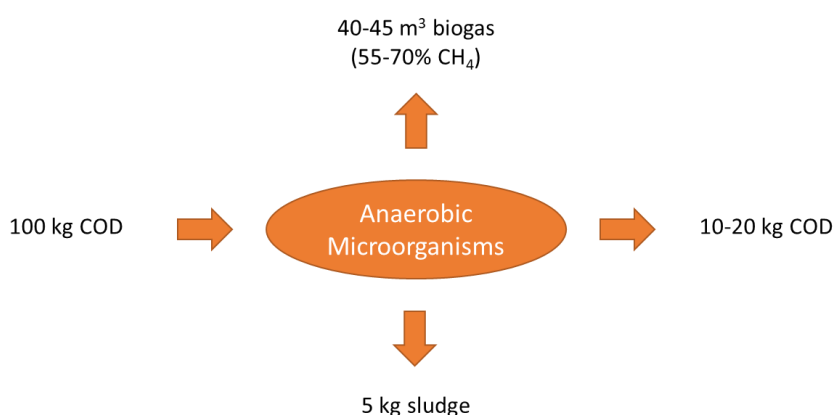
Figure 1.1. Carbon balance in the anaerobic treatment of wastewater (COD=Chemical Oxygen Demand).

The anaerobic process can be used for the treatment of all organic compounds, being more efficient and economical for the easily biodegradable wastewater, such as domestic wastewater. Thus, during the last decades, the implementation of the anaerobic process has presented a substantial increase for domestic sewage treatment in warm-climate regions, mainly due to energy savings and low sludge management costs, compared to typical aerobic treatment methods. In fact, a maximum potential energy recovery up to 1.9 kWh/m^3 has been reported from the treatment of the organic matter of domestic wastewater (McCarty et al., 2011).

One of the main characteristics of the anaerobic processes is the low growth rate of the anaerobic microorganisms, which is advantageous from the point of view of the sludge production (low), but disadvantageous from the point of view of the start-up and achievement of high organic removal rates in the anaerobic reactors. Therefore, a high solids retention time (SRT) is needed to increase the biomass concentration in the system and guarantee the growth of anaerobic microorganisms in the anaerobic reactors. One efficient alternative to achieve high SRTs is the use of granular sludge, and therefore the use of Upflow Anaerobic Sludge Blanket (UASB) reactors appears as the most attractive alternative for the implementation of anaerobic granular processes.

The main advantage over other type of reactors is that UASB reactors present a high biomass retention capacity which allows achieving extremely high loading rates, together with low requirements of area and reactor size. Furthermore, UASB reactors are easy to manage from the point of view of their hydraulic operation, which have presented them as a popular technology for wastewater treatment. In fact, successful operations of anaerobic treatment in UASB reactors were demonstrated since the last decade of the 20th century, becoming a mature technology successfully applied for different types of wastewaters such as food industry, beverage industry, pulp and paper industry, brewery, among others. Lately, many researchers

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around the world have recommended the UASB technology for the domestic wastewater treatment in tropical and subtropical regions. Hence, UASB reactors appeared as a very attractive alternative for the wastewater treatment of the HYDROUSA project due to its operation simplicity and its organic matter removal potential. Table 1.1 shows the main advantages and disadvantages of this technology.

An UASB reactor consists of a tank where the feed (wastewater) flows upwards through a dense sludge bed with high anaerobic microbial activity. A basic scheme of an UASB reactor is depicted in Figure 1.2. The sludge bed occupies about half the volume of the reactor and consists of granules or highly sedimentable flocs. The solids profile in the reactor varies from very dense and granular particles close to the bottom ('sludge' in Figure 1.2) to more dispersed and light particles close to the top ('sludge bed' in Figure 1.2). The wastewater enters from the bottom of the UASB reactor and the effluent leaves the reactor through a settling zone at the top. Thus, the organic matter removal takes place in all reaction areas. The gas produced leaves the reactor through the top.
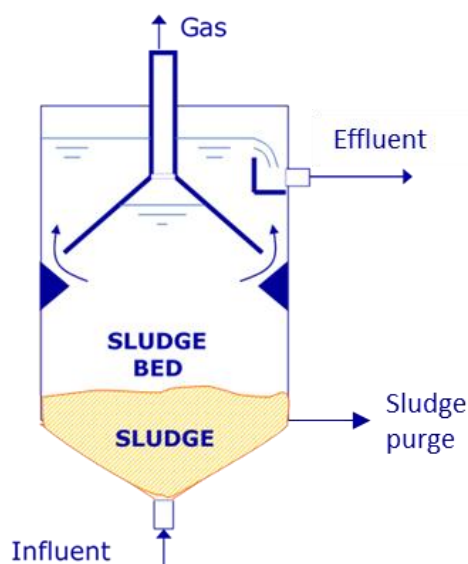
Figure 1.2. Basic scheme of an UASB rector for performing anaerobic treatment.

UASB reactors present a gas-liquid-solid (GLS) separator in the upper part (Figure 1.2). The GLS separator consists of a collection dome which must guarantee optimal conditions for the settling of the particles that escape from the sludge bed, avoiding their wash out from the system. Thus, the SRT can be maintained high in the reactor despite of a reduced hydraulic retention time (HRT). The GLS separator also guarantees a proper collection and release of the biogas produced through the dome.

To guarantee an appropriate granule formation and good settling properties of the granular sludge, the UASB reactor must maintain an appropriate mixing, which is achieved by the liquid and gas flows. A mechanical mixing is not used in UASB reactors to avoid granules deterioration, which in addition helps reducing investment costs. It is well known that the liquid upflow velocity (V_{up}) is a key parameter to maintain granulation in UASB reactors and to guarantee enough mixing to avoid external mass transfer problems during operation. UASB reactors usually operate at liquid V_{up} in the range of 0.5–1 m h^{-1}. If liquid V_{up} cannot be maintained high enough to guarantee a proper operation in the UASB reactor, a liquid recirculation can be performed from the top to the bottom of the reactor. By including such liquid recirculation not only the liquid V_{up} is increased but also a dilution of the influent takes place, which in some cases of highly polluted influents

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can be advantageous for the reactor operation. The main disadvantage of implementing a liquid recirculation is the increase of the operation costs associated to the liquid pumping.

Table 1.1. Advantages and disadvantages of the technology implemented

ADVANTAGES	DISADVANTAGES
Low sludge production	Anaerobic microorganisms are more vulnerable to inhibition and toxicity than aerobic microorganisms
Low energy consumption (just influent pumping)	Slow start-up if matured anaerobic granular sludge is not available as inoculum
Low footprint required	Need of post-treatment for pathogens removal and, in some cases, nutrient (N and P) removal
Low investment costs	Possible generation of bad odours and corrosion problems related to the production of H_2S
Biogas production (energy recovery)	Temperature must be maintained within 15–35 °C
Relatively quick start-up (<1 week) if matured anaerobic granular sludge is available as inoculum	Alkalinity addition can be required
Possibility of biomass preservation during reactor shutdowns (such as shutdowns for maintenance operation)	
Ability to withstand organic shock loads	
High efficiency even at high organic loads, which allow for lower reactor volumes	
Wide applicability (large and small scale)	
Very low nutrient removal	
No need of chemicals	
Potential for low carbon footprint	

2. UASB SYSTEM

2.1. Technical description

The anaerobic treatment with an UASB reactor is proposed in the HYDROUSA project to treat a domestic wastewater at community level. The demonstration site chosen is the Wastewater Treatment Plant (WWTP) of Antissa, in the island of Lesvos, Greece.

The anaerobic wastewater treatment takes place in an UASB reactor, triggering the production of biogas and a low amount of sludge. The biogas will be treated to remove the hydrogen sulphide and then will be upgraded to remove CO_2 and convert it in methane, which could be subsequently used as a fuel in a vehicle used the dissemination of the HYDROUSA project. The chart flow of the system proposed for the treatment of the domestic wastewater and the Piping and Instrumentation Diagram (P&ID) of the installation are presented in the Annex.

The UASB reactor will be fed by the pre-treated domestic wastewater arriving to the Antissa domestic WWTP. Pre-treatment of wastewater in Antissa WWTP is implemented in a typical pre-treatment system consisting of an inlet chamber, a fine screening unit and a grease and grit removal unit. This configuration is a typical pre-treatment unit very often used in full scale UASB applications. The characteristics of this influent (from now pre-treated domestic wastewater) are detailed in Section 2.2. Part of this pre-treated domestic wastewater will be stored in a pumping tank for feeding the UASB reactor.

To achieve a stable and successful operation of the anaerobic process in the UASB reactor, temperature must be maintained in the reactor within the range of 15-35 °C. The available wastewater temperature data of the Antissa WWTP shows that this limitation is accomplished, since influent temperature is usually higher than 20 °C. Nevertheless, due to the temperature decreases during the winter period, an electric resistance will be installed in the pumping tank to heat the wastewater whenever it is needed to sustain certain temperature in the reactor (e.g. periods of intense cold during winter or even during the start-up period, when biomass is being acclimated).

The influent is pumped from the pumping tank to the UASB reactor where the anaerobic treatment is implemented. Then, the effluent is collected in an effluent tank and will feed the constructed wetlands system (Deliverable 3.2). In this project, a liquid recirculation will be implemented in the UASB reactor. This recirculation will be activated when the influent flow is not high enough to maintain a minimum V_{up} of 0.5 m h^{-1}. Such situation is expected to occur during the start-up of the system and probably during winter. The effluent tank is installed to ease the UASB reactor liquid recirculation. If recirculation is activated, the effluent is pumped from this tank to the bottom of the UASB reactor.

The biogas produced during the anaerobic treatment is collected in the upper part of the UASB reactor and derived to a gasometer. All biogas pipelines and the gasometer present the necessary safety equipment (safety valves, flame arrester, pressure sensors, etc). Biogas is composed by methane, but also contains other undesirable compounds as carbon dioxide and hydrogen sulphide, which must be removed in order to use the biogas produced as a fuel. In this project, a filter of activated carbon will be incorporated to remove the H_2S from the biogas, and an upgrading system will be installed to remove the CO_2.

2.2. Design criteria and assumptions

2.2.1. Influent characteristics

The UASB system will be fed with pre-treated wastewater from Antissa WWTP. The quality characteristics in the influent fed to the UASB are therefore identical to the influent characteristics of wastewater of Antissa WWTP. Table 2.1 shows the main quality characteristics of the influent wastewater of Antissa WWTP, which present typical values of domestic wastewater.

Table 2.1. Main characteristics of the influent entering the urban WWTP of Antissa.

Parameter	Value*	Units
Temperature	23 ± 2	°C
pH	7.3 ± 0.3	-
Conductivity	1164 ± 223	µS/cm
Chemical Oxygen Demand, COD	578 ± 83	mg/L
Biological Oxygen Demand (5 days), BOD_5	331 ± 56	mg/L
Total Suspended Solids, TSS	272 ± 39	mg/L
TKN	42± 9	mg/L
Ammonium, NH_4-N	32 ± 8	mg/L

*(Average values were calculated from data collected between July 17' and September 18')

The UASB system is designed to provide a treatment capacity of 100 m^3/d for the summer period and 10 m^3/d for the winter period. Table 2.2 summarizes the main data for the design of the UASB system.

Table 2.2. Design data for UASB

PARAMETER	SITUATION A (WINTER)	SITUATION B (SUMMER)	UNITS
Flow rate	10	100	m^3/d
COD concentration	578	578	mg/L
BOD_5 concentration	331	331	mg/L
TSS concentration	272	272	mg TSS/L
Temperature	14 – 18	23 – 26	°C
Organic load	5.78	57.8	kg COD/d

2.2.2. Effluents characteristics

The biological treatment of domestic wastewater with an UASB reactor produces different types of effluents, whose management is considered in different tasks of the HYDROUSA project (Table 2.3). The amounts produced and the characteristics of these effluents were estimated considering the influent to be treated, and are presented in this section.

Table 2.3. Effluents produced during the anaerobic treatment of domestic wastewater in the UASB reactor

Effluent	Type	Amount produced	Management
Treated wastewater	Liquid effluent	Summer: 100 m³/d Winter: 10 m³/d	Subsequent Constructed Wetlands system (D3.2)
Sludge	Sludge	Summer: 2.5 kgSS/d Winter: 0.25 kgSS/d	Subsequent Composting System (D3.6)
Biogas	Gaseous effluent	Summer: 24 m³/d Winter: 2.4 m³/d	Biogas upgrade to CH₄ for use as fuel for a promotional vehicle (Section 3)

The anaerobic treatment with UASB reactors usually achieves removal efficiencies of 70-80% of the COD and TSS content. Hence, to meet the treated effluent discharge/reuse legislation, these types of systems are frequently followed by post-treatment systems, such as: constructed wetlands, biotrickling filters, physicochemical systems, or activated sludge systems, among other possibilities. In the HYDROUSA project, the UASB reactor will be followed by a constructed wetland (CW) system. The organic matter and solids content of the feed stream are key parameters for CW systems, and therefore, these parameters were considered when designing the UASB. Thus, the reactor was designed for achieving a **liquid UASB effluent** with the following characteristics:

- COD concentration: 173 mg/L
- Suspended Solids concentration: 90 mg/L
- Nitrogen and phosphorous concentration: nutrients are not expected to be removed in appreciable quantities during the anaerobic treatment (some amount will be consumed for the microbial growth, although it can be considered negligible). An ammonia nitrogen concentration of 30 ± 10 mg NH_4-N/L should be expected in the UASB effluent, while the respective values for phosphorus will be around 4-8 mg P/L.
- pH: close to 7. Since domestic wastewater presents a high alkalinity, and therefore high buffering capacity, pH is not expected to present important changes during anaerobic treatment.
- Oxygen concentration: approx. zero (anaerobic influent)

2.3. Process design calculations

Wastewater pumping tank

A new pumping well will be constructed next to the existing pre-treatment facilities of Antissa WWTP where part of the pre-treated wastewater will be collected and subsequently fed to HYDRO 1. This tank will be used

as equalization tank for influent and will allow to maintain a stability of the inflow to the UASB reactor, while giving a high versatility to the system. Furthermore, an electric resistance will be installed in this tank to heat the influent wastewater if needed.

The wastewater pumping tank will present a volume of at least 2 m³ and all the necessary manholes and pipelines to adapt it to the installation.

UASB reactor: Initial Volume Calculation

The volume of the UASB reactor has been defined according to the hydraulic retention time (HRT) required to guarantee the domestic wastewater treatment (Equation 1). According to literature, typical values of HRT are between 5–10 h for municipal wastewater at temperatures of 16 – 26 °C. A value of **HRT of 10 h** has been considered in order to be conservative and to ensure an effective organic matter removal even under the most unfavourable situations: peak organic loads during summer period and low temperatures during winter.

$$\boldsymbol{Volume} = Q \cdot HRT = 100\,\frac{m^3}{d} \cdot 10\,h \cdot \frac{d}{24\,h} = 42\,m^3 \qquad \text{(Eq. 1)}$$

where,

      Q = inflow
      HRT = hydraulic retention time

Reactor Shape

UASB reactors can be built in parallelepiped or cylindrical shape. Factors such as economical cost, reactor size, materials availability, space availability, etc. should be considered during the decision of the reactor shape. The circular shape involves higher structural stability and smaller perimeter than a rectangular shape of the same surface area. However, at industrial scale, when reactor volumes are high, rectangular or even square shapes may be more advantageous for construction issues, since they can be built in modules and a wall can serve two contiguous modules. Overall, UASB reactors of a volume lower than 300 m³ usually present circular shape, whereas bigger reactors than these are mainly built in rectangular shape. Considering the volume of the UASB reactor presented here (c.a. 42 m³), a circular shape was chosen.

The internal parts of the UASB reactor which require special considerations are:
- The gas-liquid-solid separator (GLS separator) and deflectors
- The biogas outlet
- The influent inlet and distributor
- The effluent outlet

The design of these internal parts is detailed in the following sections of this report.

Reactor Dimensions

On one hand, UASB reactors can be designed according to two criteria: (i) based on the organic loading criteria or (ii) based on the hydraulic loading criteria.

In a reactor limited by the organic load (high COD concentrations and low flow rates), the biomass could not be able to degrade all the present organic load. UASB reactors usually operate at values of organic volumetric load rate between 2-40 kgCOD/m³d. In the case of typical domestic wastewater, the organic matter concentration is low (<1000 mg COD/L) and, thus, the applied volumetric organic load is also very low (usually lower than 4 kg COD/m³/d). Since the use of higher volumetric organic loading rates would result in excessive hydraulic loads and, consequently, in too high liquid V_{up} (V_{up} should be lower than 1 m h⁻¹), in these cases, the

reactor is always designed based on the volumetric hydraulic load and not on the organic load. Therefore, the UASB reactor presented in the HYDROUSA project was designed according to the hydraulic limitation to guarantee an adequate V_{up}. However, a check of the organic loading rate (OLR) can be made. For this calculated volume of 42 m² the OLR should be less than 5 kgCOD/m³d. In fact for V= 42 m³ and for the measured inlet COD concentration of raw sewage the organic loading rate is less than 1.4 kgCOD/m³d.

When considering wastewater with low organic loading rates, such as the domestic wastewaters, the height to diameter ratio is typically high. A low sectional area facilitates the feeding to the reactor (better influent distribution), and the accumulation of biogas through the height of the reactor contributes to the formation of a turbulent flow (better mixing).

Hence, considering the typical range of V_{up} in UASB reactors (0.5–1.5 m h^{-1}), a high height to diameter ratio, and the most unfavourable conditions regarding organic load (summer period), a value of V_{up} of 0.6 m h^{-1} was selected. The calculation process to determine the reactor dimensions is according to Equations 2a & 2b; where S is the reactor sectional area, Q is the inflow, V_{up} is the liquid upflow velocity and d is the reactor diameter.

$$S = \frac{Q}{V_{up}} = \frac{100\,\frac{m^3}{d}\,\frac{d}{24\,h}}{0.6\,\frac{m}{h}} = 6.94\,m^2 \qquad \text{(Eq. 2a)}$$

$$S = \pi \cdot \frac{d^2}{4} = 6.94\,m^2 \qquad \text{(Eq. 2b)}$$

$$\boldsymbol{Diameter} = 2.97\,m$$

The height of the reactor can be easily calculated if the area (Equation 2) and the volume (Equation 1) are known. Thus, the **height** of the reactor is 6.0 m.

Gas-Liquid-Solid Separator and Deflectors

The design of the Gas-Liquid-Solid (GLS) separator is one of the most critical points of the design of UASB reactors. The GLS separator must provide:
 – Enough gas-liquid interface inside the gas dome, allowing the easy release of the gas entrapped in the sludge
 – Enough settling area outside the dome, to guarantee the proper surface overflow rate
 – Enough dome area to avoid liquid turbulence, which can lead to a bad solids separation
 – Proper sludge retention, allowing the solids to return to the bottom of the reactor

The GLS separator must be designed according to the characteristics of the wastewater treated, the type of sludge, the organic load, the expected biogas production and the dimensions of the reactor. It can present cylindric or rectangular shape depending, mainly, on the size of the reactor. For small and cylindrical UASB reactors, such as the reactor of the present project, a conical shape is more adequate.

Deflectors must be installed immediately below the aperture to the GLS separator, to enable the separation of the biogas and to allow only liquid and solids pass through the settling compartment. These deflectors avoid

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the presence of biogas bubbles (which trigger turbulence and bad sedimentation of solids) in the settling zone of the GLS separator.

Table 2.4 shows the considerations that must be applied when designing a GLS separator and deflectors and the selected values calculated for the present HYDROUSA case.

Table 2.4. Boundaries applied for the design of the GLS separator and deflectors of the UASB reactor

	BOUNDARY	SELECTED VALUE
Liquid upflow velocity at the bottom of the GLS separator (V$_{UP,GLS}$)	< 4 m/h	1 m/h
Ratio between separator height and reactor height	0.15 – 0.30	0.25
Separator diameter	Defined by the reactor diameter and V$_{up,GLS}$*	1.88 m
Separator angle (angle between the separator and the transversal area)	45 – 60 °	58 °
Separator and deflector overlap	15 – 20 cm	20 cm
Deflector angle	45 °	45 °

*Once the liquid V$_{up}$ at the bottom of the GLS separator is selected, the cross-sectional area of liquid passage can be easily determined, and thus, the diameter of the separator. The calculation is detailed in Equations 3 and 4.

$$S_{liq} = \frac{Q}{V_{up,GLS}} = \frac{100 \frac{m^3}{d} \frac{d}{24\,h}}{1 \frac{m}{h}} = 4.17\,m^2 \tag{Eq. 3}$$

$$S_{sep} = S_{reactor} - S_{liq} = 2.78\,m^2$$

$$S_{sep} = \pi \cdot \frac{d^2}{4} = 2.78\,m^2 \tag{Eq. 4}$$

$$\boldsymbol{d_{sep} = 1.88\,m}$$

Biogas Outlet

The main restriction of the biogas outlet design regards to the minimum biogas flow required to pass through it, defined by the *biogas release rate*. The biogas release rate should be high enough to overcome a possible

scum layer, but low enough to quickly release the gas from sludge without dragging it, avoiding the accumulation of sludge in the gas piping (Fernandez-Polanco and Seghezzo, 2015). Thus, the maximum biogas release rate must be between 1–5 m^3 of biogas per m^2 of area and per hour. In the design of the UASB reactor of this project, the value selected was 2 m^3 of biogas per m^2 of area and per hour.

Hence, the biogas outlet was designed to guarantee the selected value of the biogas release rate. An estimated biogas production of 24 m^3/d was calculated for the summer period, however, considering the possible COD peaks during the operation of the installation, a biogas production of 30 m^3/d was selected for a safety design of the biogas outlet. The **diameter of the biogas outlet** dome which guarantees a biogas release rate of 2 m^3 of biogas per m^2 of area and per hour is 0.9 m.

Influent distributors

A good design of the influent inlet distributor is important to:
  – Establish optimum contact between the sludge available inside the reactor and the wastewater admitted
  – Avoid preferential flows of the wastewater through the sludge bed
  – Avoid dead zones in the sludge bed

This is particularly imperative in the case of the treatment of domestic wastewater, since the biogas production is expected to be quite low because of the low COD concentration and low temperature of the wastewater, and thus, biogas production is not expected to guarantee the appropriate mixing in the UASB reactor.

The influent could be introduced through the top or through the bottom of the reactor, which depends mainly on the wastewater solids content. In the present case, with pre-treated domestic wastewater as influent (relatively low solids content), a pumped feed through the bottom was chosen to introduce the influent into the UASB reactor. A **lateral inlet** at 20 cm of the bottom of the reactor with different inlet points was selected to distribute the influent.

The use of different inlet points is needed to achieve a homogeneous distribution of the influent through the sludge bed of the UASB reactor. The higher the number of inlet points, the better the influent distribution, and thus, the better the removal efficiency of the system. A total of **5 distributors** will be installed, according to the diameter of the reactor and the distance between the inlet points.

According to bibliography (Fernandez-Polanco and Seghezzo, 2015), the diameter of the distributors must be between 75–100 mm to avoid clogging, but with a nozzle at the bottom with a diameter around 40-50 mm to guarantee enough flow velocity in the piping exit (>0.4 m/s). Indeed, the linear velocity and the diameter of the pipeline are the main parameters to consider when a pipeline is designed. The values recommended before are typical values for industrial installations which usually present high wastewater flow rates, however in the case of the present project, with low flow rates (100 m^3/d as the maximum value), lower diameters are needed for achieving flow velocities high enough to avoid clogging.

Table 2.5 shows some of the possibilities studied during the design of the pipelines of the influent distributors. Since the maximum wastewater flow is 100 m^3/d, the flow through each influent distributor will be 20 m^3/d as maximum. This value is extremely low to install a pipeline with a diameter of 75 mm, since the flow velocity will result in 0.05 m/s, which is an extremely low value which will not help to avoid clogging in the pipeline. Ideally, a pipeline diameter of 25 mm would guarantee a flow velocity high enough to avoid clogging, nevertheless it could seem a low diameter for the UASB design standards. Hence, a compromised situation was chosen for the present project: a pipeline diameter of 32 mm for the five influent distributors. This value

is high enough to avoid clogging in the system. The liquid velocity resulted (Table **2.5**2.5) is still quite low, although it is in the order of magnitude adequate to avoid clogging. In any case, during operation periods when the flow rate will be lower than the maximum (e.g. during winter), the flow velocity will be increased by activating the internal liquid recirculation which the UASB reactor will have.

The same argumentation was done to choose the size of the nozzles. Three nozzles of 20 mm of diameter will be present in each influent distributor. The flow velocity through each nozzle will be 0.25 m/s, which is an appropriate value for this application. In any case, a pressure indicator will be installed in the pipeline before the influent distributor. Thus, an unexpected increase in pressure will indicate the clogging of an influent distributor pipeline. If this occurs, the system has a series of valves which allows the pass through one single influent distributor pipeline. By passing water at maximum flow through the single pipeline, the clogging should be overcome.

Table 2.5. Diameters evaluated during the design of the pipelines of the influent distributors

Pipeline diameter (mm)	Maximum flow (m³/d)	Flow velocity (m/s)
75	20	0.05
32	20	0.3
25	20	0.5

Effluent collection
The effluent will leave the UASB reactor by overflow through the perimeter of the reactor, avoiding the use of a withdrawal pump, which helps to maintain low costs of operation. A proper area of settling must be provided to avoid the solids presence in the effluent. Some scum and sludge accumulation could occur in the surface of the liquid in the top of the reactor, and thus, a scum baffle and a hatch to perform maintenance and cleaning tasks should be installed.

Sludge production
A low amount of **anaerobic sludge** is expected to be produced during the wastewater treatment process (approx. 0.06-0.07 kg sludge/kg COD removed). Hence, the sludge production is expected to be around 2.5 kgSS/d in the summer period, whilst this value will be reduced around 0.25 kgSS/d during winter.

Anaerobic sludge solids concentration is usually high, achieving values up to 30 g/L. Hence, the volume of sludge produced would be around 83 L/d in summer period and 8.3 L/d during winter. A tank for sludge storage will be incorporated to the installation to guarantee a proper storage of sludge until its management (feeding to the composting unit) is performed. The tank volume was selected to guarantee a maximum storage of 1 week, to avoid important odour generation due to the sludge storage. Alternatively, to reduce the sludge storage, the sludge purge of the reactor can be done the same day that the feeding of sludge to the composting unit will be performed.

Biogas production
The calculation of biogas production is based on the mass of organic matter removed from wastewater (Equations 1 and 2, Kiely, G., 1997). It is well known that stoichiometrically methane production equals to 0.35 m³/kgCOD removed. By taking into account an average CH_4 content of 60% in biogas, a biogas production for the summer and winter period can be calculated as follows:

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- Mass of COD removed: 40.5 kg/d (summer) - 4.1 kg/d (winter)
- CH_4 production: 14.2 m^3/d (summer) - 1.4 m^3/d (winter)
- Biogas production: 24 m^3/d (summer) - 2.4 m^3/d (winter)

For the design of the biogas processing line a safety factor of 25% is anticipated to account for possible peak loads. Therefore, the design of the biogas treatment line will be based on a maximum production of 30 m^3/d.

Design Summary

Once all the design parameters were calculated, the drawings of the UASB reactor were performed according to the calculated values and the construction limitations. Such construction limitations led to make some modifications of the previously calculated dimensions. Table 2.62.6 presents the summary of the final design parameters and the Annex contains the final drawings of the UASB reactor.

Table 2.6. Main design parameters of the proposed UASB reactor

STAGE	PARAMETER	VALUE
DESIGN	Flow rate	100/10 m^3/d (summer/winter)
	COD influent concentration	578 mg/L
	TSS influent concentration	272 mg/L
	COD effluent concentration	173 mg/L
	TSS effluent concentration	90 mg/L
	OLR	1.4 kg COD/m^{3}d
	COD removed	40.5/4.1 kg COD/d (summer/winter)
	Sludge production	2.5/0.25 kg SS/d (summer/winter)
	Biogas production	24/2.4 m^3/d (summer/winter)
UASB REACTOR	Total volume	44.5 m^3
	Liquid volume	40.9 m^3
	Shape	Cylindrical
	Diameter	3.0 m
	Height	6.0 m

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	Hydraulic Retention Time (considering the total volume)	10.2 hours
	Hydraulic Retention Time (considering the liquid volume)	9.3 hours
	Liquid Upflow Velocity	0.6 m/h
GLS SEPARATOR	Shape	Cylindrical
	Area	2.8 m^2
	Number of separators	1
	Diameter	1.9 m
	Angle	58 °
BIOGAS OUTLET	Total area of biogas release	0.6 m^2
	Number of outlets	1
	Dome diameter	0.9 m
	Biogas release rate	2 m^3/m^{2}h
INFLUENT DISTRIBUTOR	Inlet	Lateral at the bottom
	Number of distributors	5
	Distributor diameter	32 mm
	Nozzles per distributor	3
	Nozzle diameter	20 mm
	Distance from the bottom	0.20 m
EFLUENT COLLECTION	Shape	Peripherical at the top
	Number of outlets	1
	Distance from the top	50 cm
	Outlet mechanism	By overflow

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Effluent tank

The effluent of the UASB reactor leaves the reactor by overflow to the effluent tank. This tank makes possible the recirculation of part of anaerobic effluent to the UASB reactor. The recirculation will be needed when the inflow is not high enough to maintain an adequate liquid V_{up} in the reactor, which will probably occur during winter. Furthermore, the effluent tank is used as an equalization tank for effluent and it allows to maintain a stability of the inflow to the subsequent post-treatment unit (CW). The effluent tank will present a volume of 1 m^3 and all the necessary manholes and pipelines to adapt it to the installation.

Biogas desulphurization unit

The H_2S present in the biogas must be removed before the biogas enters into the upgrading system, to avoid corrosion and/or malfunction of the upgrading and/or excessive maintenance (and cost associated). Nowadays, different technologies are available to successfully achieve this H_2S removal, which can be categorized as physicochemical or biological technologies.

On one hand, physicochemical technologies, such as adsorption or reactive absorption, present high efficiencies. However, the requirements of packing material substitution and the consumption of chemical reagents can make them as high cost demanding systems. On the other hand, biological systems, which take advantage of the metabolism of certain microorganisms that use H_2S for their growth, present much lower operating costs, since the reagent dosage and packing material substitution requirements, are practically reduced to zero. Biological systems can achieve similar removal efficiencies to conventional physicochemical systems although they cannot be used if biogas contains toxic compounds for the microorganisms.

In any case, considering the quality and quantity of biogas produced in the HYDRO1 site, both types of technologies could be used. However, the scale-factor (small scale) influences a lot the selection of one technology or another. To choose the more suitable treatment for the present project, two technologies have been compared: a physical treatment of adsorption with activated carbon, versus a biological treatment with a biotrickling filter (BF).

Table 2.72.7 presents some issues that have been considered to make the choice of one system or the other. The advantages and disadvantages presented in this table are specific for the current case, and it might be different, even opposed, in another case study.

The activated carbon filter is located downstream of the UASB reactor and the gasometer, working under positive pressure. The dimensions of the activated carbon filter are detailed in Section 2.4.

Considering a typical hydrogen sulphide concentration and the biogas production of the UASB reactor, a filter with 50 kg of activated carbon will be enough to remove the H_2S from the biogas. In addition, the activated carbon substitution is not expected to be carried out during the development of the HYDROUSA project.

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Table 2.7. Comparison of implementing an activated carbon system versus a biotrickling filter system for the H₂S removal in the biogas produced in the HYDRO1 site. (Red: not suitable; Purple: suitable; Green: fairly suitable).

	Activated Carbon Adsorption	Biotrickling Filter
Compactness	High	Low
Packing material substitution	High	Low
Investment costs	Low	High
Operational costs	Low	Low
Robustness during process stops or low biogas production	Yes	No
Maintenance needs	Low	Medium

2.4. List of operation units – specifications of electro-mechanical equipment

The main operation units with its corresponding P&ID tag and its specifications are presented in this section.

Equipment associated to the pumping of the wastewater to the UASB reactor

1 Submerged pump for influent pumping to the wastewater pumping tank (PS01)

–	Brand:	EBARA
–	Model:	Right 75 M A
–	Flow:	6 m³/h
–	Material:	Stainless Steel AISI 304
–	Power:	0.55 kW
–	Velocity:	50 Hz
–	Protection:	IP68

1 Electric resistance (RE01)

–	Brand:	Electricfor
–	Model:	CR212II0060 M77 LIR – 589
–	Power:	6 kW
–	Material:	Tube: AISI 316L

1 Wastewater pumping tank (TA02)

–	Volume:	2150 L
–	Shape:	Cylindric
–	Height:	1740 mm
–	Diameter:	1400 mm
–	Material:	GFRP (Glass-Fiber Reinforced Plastic)
–	Manhole:	DN40

1 Centrifugal pump for influent pumping to UASB (PC01)

–	Brand:	EBARA
–	Model:	JEX 080
–	Flow:	4 m^3/h
–	Material:	Stainless Steel AISI 304
–	Power:	0.6 kW
–	Velocity:	50 Hz
–	Protection:	IP54

1 Centrifugal pump for effluent recirculation in the UASB (PC02)

–	Brand:	EBARA
–	Model:	JEX 080
–	Flow:	4 m^3/h
–	Material:	Stainless Steel AISI 304
–	Power:	0.6 kW
–	Velocity:	50 Hz
–	Protection:	IP54

1 Effluent recirculation tank (TA03)

–	Volume:	1000 L
–	Shape:	Cylindric
–	Height:	1215 mm
–	Diameter:	1400 mm
–	Material:	GFRP (Glass-Fiber Reinforced Plastic)
–	Manhole:	DN40

UASB reactor

1 Anaerobic reactor (R01)

–	Volume:	44 m^3
–	Type:	UASB
–	Material:	AISI 316
–	Height:	6.3 m
–	Diameter:	3 m
–	Shape:	Cylindric with an internal conic separator

Equipment associated to the biogas line

1 Gasometer (GA01)

–	Volume:	4 m^3
–	Type:	Vertical
–	Pressure:	25 mbar
–	Product stored:	Biogas

1 Flame arrester (FA01)

–	Brand:	LUPI or similar
–	Housing material:	Aluminium
–	Internal elements:	Stainless steel
–	Connection:	Flanged connection
–	Homologation:	ATEX

1 Activated carbon filter for biogas desulphurization (BF01)

–	Total volume:	280 L
–	Activated carbon:	50 kg
–	Activated carbon volume:	113 L
–	Height:	1 m
–	Diameter:	0.6 m

Equipment associated to the produced sludge line

1 Tank for sludge storage (TA04)

–	Volume:	500 L
–	Shape:	Cylindric

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2.5. List of sensors – meters – automation/control strategy

Sensors/meters associated to the pumping of the wastewater to the UASB reactor

1 Pressure sensor in the pre-filter pipeline (P01)

– Brand:	IFM
– Model:	PG2795
– Range of measurement:	-1 to 4 bar
– Connection:	M12
– Operating voltage:	18-32 DC
– Analogical output:	4-20 mA
– Protection:	IP 67/IP 69K

1 Temperature sensor for the wastewater pumping tank (TI01)

– Brand:	IFM
– Model:	TN2511
– Type:	PT1000
– Range of measurement:	0-150 °C
– Analogic output:	4-20 mA
– Operating voltage:	18-32 DC
– Protection:	IP 67

1 Level sensor for the wastewater pumping tank (LI01)

– Brand:	IFM
– Model:	PI2789
– Rang of measurement:	0-100 mbar
– Fluid temperature:	0-125 °C
– Connection:	Threaded connection G 1
– Analogic output:	4-20 mA
– Operating voltage:	20-32 DC
– Protection:	IP 67/IP 68/IP 69K

1 Pressure sensor in the influent pipeline (P02)

– Brand:	IFM
– Model:	PG2795
– Range of measurement:	-1 to 4 bar
– Connection:	M12
– Operating voltage:	18-32 DC
– Analogical output:	4-20 mA
– Protection:	IP 67/IP 69K

1 Magnetic-Inductive flow meter in the influent pipeline (F01)

– Brand:	IFM
– Model:	SM8000
– Rang of measurement:	0,29 to 144 m^3/d
– Fluid temperature:	0-60 °C
– Analogic output:	4-20 mA
– Operating voltage:	18-30 DC
– Connection:	Threaded connection G 1
– Protection:	IP 67

1 Level sensor for the effluent recirculation tank (LI02)

– Brand:	IFM
– Model:	PI2789
– Rang of measurement:	0-100 mbar
– Fluid temperature:	0-125 °C
– Connection:	Threaded connection G 1
– Analogic output:	4-20 mA
– Operating voltage:	20-32 DC
– Protection:	IP 67/IP 68/IP 69K

1 Magnetic-Inductive flow meter in the recirculation pipeline (F02)

– Brand:	IFM
– Model:	SM8000
– Rang of measurement:	0,29 to 144 m^3/d
– Fluid temperature:	0-60 °C
– Analogic output:	4-20 mA
– Operating voltage:	18-30 DC
– Connection:	Threaded connection G 1
– Protection:	IP 67

Sensors/meters associated to the UASB reactor

1 Temperature sensor (TI02)

– Brand:	IFM
– Model:	TN2511
– Type:	PT1000
– Range of measurement:	0-150 °C
– Analogic output:	4-20 mA
– Operating voltage:	18-32 DC
– Protection:	IP 67

1 pH sensor (pHI01)

– Brand:	Seko
– Model:	SPH-3-WW
– Material:	Glass
– Reference cell:	Gel
– Range of measurement:	2–12
– Fluid temperature:	0–80 °C
– Pressure:	< 6 bar

1 Redox sensor (RI01)

– Brand:	Seko
– Model:	9900105033
– Type:	Glass-Pt
– Range of measurement:	-2000 to 2000 mV
– Range of pressure:	< 6 bar
– Analogic output:	4-20 mA

Sensors/meters associated to the biogas line

1 Biogas flowmeter (F03)

– Brand:	Ritter
– Model:	TG10-PVC-PVC
– Range of measurement:	20-1200 l/h

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2 Pressure sensors (P03, P04)

–	Brand:	IFM
–	Model:	PI008A
–	Homologation:	ATEX
–	Range of measurement:	0-250 mbar
–	Operating voltage:	18-32 DC
–	Analogical output:	4-20 mA
–	Protection:	IP 67/IP 68/IP 69K

Electrical Panel and Control Panel

Still undefined

2.6.   Benefits and limitations

Beyond the benefits of using an anaerobic process for the treatment of domestic wastewater, associated to energy savings and cost reduction which have been explained, the implementation of such treatment by using an UASB reactor presents noticeable advantages over the use of other reactors (Table 2.82.8). In this project, the area requirements of the plant are very low (approx. 25 m^2, which supposes approx. 0.25 m^2 per m^3/d of wastewater treated). Furthermore, there is no need of using chemical reagents for achieving a successful UASB operation, although a filter of activated carbon is used for the biogas desulphurization. At large scale (industrial scale), the desulphurization could be easily performed by using a biotrickling filter, reducing almost to zero the reagent dosage and packing material substitution requirements. However, in the HYDROUSA project, with a 4-year application, the implementation costs associated to a BF system make it not adequate. Still, the activated carbon filter is not expected to be replaced during the entire development of the project.

Table 2.8. Main advantages of the use of UASB reactors for the anaerobic wastewater treatment

UASB Reactor Advantages
High biomass retention capacity which allows achieving extremely high loading rates
High system compactness, with low requirements of area and low reactor size
Potential for energy recovery (as biogas)
Low and stable sludge production
Low construction and operating costs
Negligible or no energy consumption (only influent pumping and, in some cases, recirculation pumping)

2.7. Description of the operation

The installation will present a control panel with a touchpad screen where the state and operation of the main equipment of the process are presented. Whatever the opened window in the touchpad screen, there will be different icons for the defined access menus at the top of the screen (Figure 2.1).
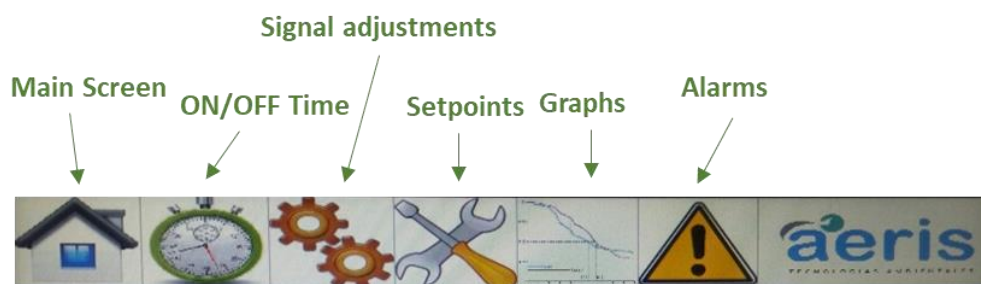

Figure 2.1. Example of main access menus located at the top of the touchpad screen

An exhaustive description of the icons and their access options will be presented in the further corresponding deliverable about the plant operation. In any case, the following general options will be present in the Control Panel of the installation:

- Synoptic Panel: a scheme of the plant with all the equipment will be in the main screen. In such panel, the operation mode of the different equipment (automatic/manual mode) and the main measured parameters (pH, redox, temperatures, etc.) will appear.
- Submenus: every equipment will present a submenu to activate the operation modes (automatic/manual) and to run or stop the equipment in manual mode.
- Graphs: all the parameters measurements will be plotted in graphs. These graphs can be consulted at any time.
- Setpoints and operation time: every parameter and equipment can be adjusted by user.
- Alarms: all the alarms occurred will be registered in the system.

2.8. Safety instructions

The equipment must be exclusively handled by qualified and/or properly trained personnel, which must provide the appropriate personal protective devices (PPD) to prevent the risks associated to the use of any equipment or to the operating environment in which it has been installed. Table 2.92.9 shows the symbols of the main personal protective devices which must be available during operation and/or maintenance of the system.

In addition to the use of PPD, to avoid any risky conditions for users or damage to the equipment, it is advisable to strictly follow the warnings and behavioural rules detailed in the equipment datasheets, together with the following indications:

- If the operation involves any risk of explosion or fire (biogas related), operators must pay special attention to: (i) carefully read the safety datasheet of products/equipment and not to expose them with other products or environments prohibited by such datasheet; (ii) isolate the working area; (iii) use fire extinguishers suitable for the materials to be used and in perfect condition.

- Users are prohibited from removing protections or circumventing safety measures, as it would reduce the installation safety level (e.g. flame arrester, sensors, etc). If users have carried out maintenance operations, they must check that the protections eventually removed have been correctly reinstalled before restarting the system.

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- Electrical and pneumatic connections to the mains must be carried out exclusively by authorized operators in accordance with the regulation in force.

Table 2.9. Personal protective devices which must be available for the wastewater treatment system

	Obligation to wear clothing tight to the body and without flounces that can get caught into the equipment. Clothing must be suitable to protect the skin from the chemicals or process liquids used.
	Obligation to use respiratory protection devices (masks) in presence of harmful vapours or gases.
	Obligation to use protection gloves for chemicals or electricity.
	Obligation to use head protection devices (helmets) if interventions are required within the perimeter of the machine.
	Obligation to use devices to prevent accidental falls (ropes), especially for operations of assembling, installation and maintenance at height.
	Obligation to use eye protection devices (goggles) if there is a risk of chemicals or process liquids splashes.

3. BIOGAS UPGRADE SYSTEM

3.1. Technical description

The biogas upgrade system aims to remove the carbon dioxide in order to produce a high purity methane gas (>96%). Currently, technologies that could be used for CO_2 removal from gas include physical and chemical absorption, Pressure Swing Adsorption (PSA), membrane separation, cryogenic separation and biological methane enrichment (Ryckebosch et al., 2011; Kasikamphaiboon et al., 2013). However, among these, CO_2 absorption using alkanolamines as chemical solvents appears to offer an interesting and practical alternative.

In this technique, CO_2 is separated from a gas stream, in this case biogas, by passing the gas stream through a continuous scrubbing system consisting of an absorber and a desorber-stripper. After absorbing CO_2 in an absorber, the amine solution is then sent to a desorber where the temperature is raised, resulting in CO_2 stripping from the amine solution (solvent regeneration). The regenerated solution is then returned to the absorber thereby creating a continuous recycling process. With the advantage of high efficiency and stability, packed column is widely used as the absorber and desorber in the CO_2 capture system (Kasikamphaiboon et al., 2013; Yu et al., 2010). In the existing industrial absorption processes, alkanolamines such as Monoethanolamine (MEA), Diethanolamine (DEA), Di-2-propanolamine (DIPA) and Methyldiethanolamine (MDEA) are commonly used (Mandal et al., 2003).

Several experiments comparing amines have been carried out, always obtaining the best results for MEA (Lin et al., 1999; Bidart et al., 2011; Biernacki et al., 2014). Although new alkanolamines and alkanolamine mixes have been developed, MEA is still the preferred chemical for CO_2 absorption. This is because MEA has a high reactivity, low solvent cost, low molecular weight (giving a high absorption capacity on a weight basis) and reasonable thermal stability (Ma'mun et al., 2007; Kasikamphaiboon et al., 2013). Moreover, MEA can be used for the simultaneous absorption of CO_2 and H_2S from the biogas (Kasikamphaiboon et al., 2013). Biernacki et al. (2014) showed that an aqueous solution of 30% MEA is the best alternative among the different alkanolamines used for biogas upgrading, taking into consideration economic, social and ecological aspects (Megido et al., 2015) .

3.2. Design data

Reaction schemes of CO_2 and $H_2 S$ with MEA
The mechanism of CO_2 absorption is not totally elucidated. However, the overall reaction of CO_2 with primary amine (RNH_2) such as MEA can be represented as in Reaction 1 (Choi et al., 2009).

$$CO_2 + 2RNH_2 \leftrightarrow RNHCOO^- + RNH_3^+ \qquad (Reaction\ 1)$$

This mechanism comprises two steps, namely, formation of the CO_2 -amine zwitterions as shown in Reaction 2, followed by base catalyzed deprotonation of this zwitterions as shown in Reaction 3:

$$CO_2 + RNH_2 \leftrightarrow RNH_2^+COO^- \qquad (Reaction\ 2)$$
$$RNH_2^+COO^- + B \leftrightarrow RNHCOO^- + BH^+ \qquad (Reaction\ 3)$$

Where, B is a base which could be amine, OH^- or H_2O.

The reaction of H_2S and MEA is reversible and instantaneous. H_2S reacts with MEA by proton transfer (Reaction 4).

$$RNH_2 + H_2S \leftrightarrow RNH_3^+ + HS^- \hspace{4cm} (Reaction\ 4)$$

The CO_2 removal from the stream of raw biogas will take place using an amine scrubber. A stripper for the regeneration of the saturated amine using heating will also be used. An aqueous solution of 30% MEA will be used as an absorber for CO_2 from the raw biogas stream. Regarding the compression of the upgraded biogas, a commercially available compressor that is capable of compressing natural gas at 207 bar, specifically modified for this application will be used.

Upgrading of biogas is necessary for the use of the compressed upgraded biogas in the automotive sector. The biogas produced during the anaerobic treatment is collected in the upper part of the UASB reactor and sent to a gasometer. All biogas pipelines and the gasometer present the necessary safety equipment (safety valves, flame arrester, pressure sensors, etc.). Biogas is mainly composed by methane, but it also presents other undesirable compounds as carbon dioxide and hydrogen sulphide, which must be removed in order to use the biogas produced as a fuel. In this project, a filter of activated carbon will be incorporated to remove the H_2S from the biogas, and an upgrading system will be installed to remove the CO_2.

3.3. Design criteria and assumptions

3.3.1 Influent characteristics

The biogas upgrade system will be fed with biogas which will be produced from UASB after removing hydrogen sulphide. Table 3.1 shows the main quality characteristics of the biogas influent.

Table 3.1. Main characteristics of the biogas influent entering to the upgrade system.

Parameter	Value*	Units
Temperature	30±2	°C
CH_4	60	Vol%
CO_2	40	Vol%
N_2	0.2	Vol%
O_2	0.1	Vol%
H_2	0.1	Vol%
H_2S	<2	ppm
C_nH_m	<2	ppm

The unit is designed to upgrade 30 m^3/d biogas for the summer period and 3 m^3/d biogas for the winter period. Table 3.2 summarizes the main data for the design of the upgrade system.

Table 3.2. Design data for upgrade system

PARAMETER	SITUATION A (WINTER)	SITUATION B (SUMMER)	UNITS
Flow rate	3	30	m^3/d
Temperature	28-30	30-35	°C

3.3.2 Effluents characteristics

The amounts produced and the characteristics of these effluents were estimated considering the influent to be treated, and are presented in this section (Table 3.3).

Table 3.3. Effluents produced during the treatment of biogas after Upgrade System

Parameter	Value*	Units
Temperature	20±2	°C
CH_4	97±1	Vol%
$H_2O_{,max}$	32	mg/Nm^3
$CO_2 + N_2 + O_2$	4	Vol%
$O_{2,max}$	1	Vol%
$H_2S_{,max}$	23	mg/Nm^3
Methanol	0	Vol%
Particulates	5	µm

Biogas upgrading and biomethane production offer new opportunities for the use of biogas and for the substitution of fossil fuels in transport sector.

3.4. Process design calculations

A simplified absorption-process scheme is shown in Figure 3.1. In this kind of scrubbers with countercurrent operation, the feed gas, in this case biogas, enters at the bottom and flows to the top (upward), whereas the absorption solvent flows in the opposite direction (downward). Inside the scrubber, CO_2 is transferred from the biogas into the solvent (lean solvent), and the solvent loaded with CO_2 (spent solvent) flows into the stripper. Inside the scrubber, the gas stream with little or no CO_2 exits the absorber at the top as biomethane. In the stripper, the spent solvent is heated by the reboiler, thereby releasing CO_2, which exits as off gas at the

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stripper top. The solvent then, almost free of CO_2 (lean solvent), flows back into the absorber (Kohl and Nielsen, 1997). As CO_2 absorption is facilitated by lower temperatures and CO_2 desorption by higher temperatures, a heat exchanger is employed to transfer heat from the lean solvent to the spent solvent.
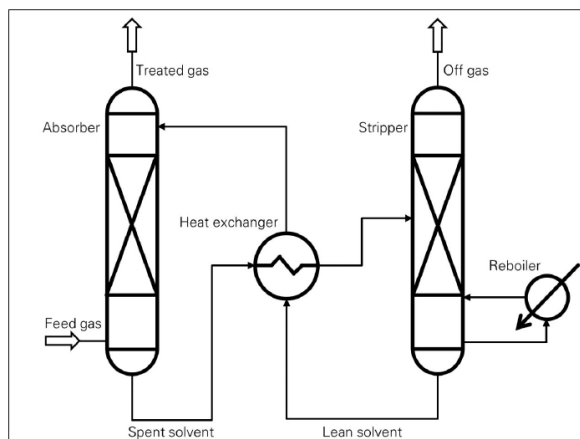

Figure 3.1. Simplified absorption-process scheme

The process design of packed absorber- scrubber with countercurrent operation and stripper columns entails the determination of the ultimate liquid flow rate, column diameter and the packed height needed to achieve a given separation, having chosen the solvent and packing type to be used. The design process is not a clear cut science but more of a combination of science and art based on experience.

Calculation of ultimate flow rate

The parameters necessary to conduct a mass and component balance across a column of the absorber are shown in Figure 3.2. These parameters are unambiguously defined in Table 3.4.
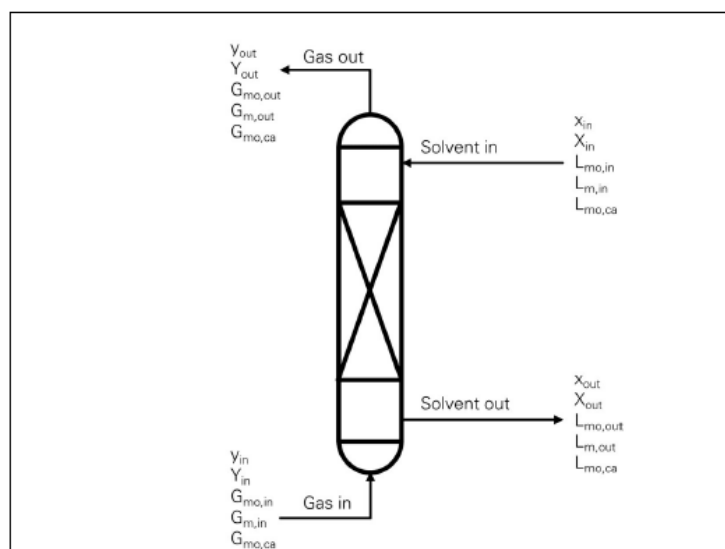

Figure 3.2. Column parameters

Table 3.4. Column parameters for a gas stream of CO_2 and CH_4 and a solvent stream of aqueous solution of 30% MEA.

Symbol	Definition	Unambiguous unit
d_{col}	Column diameter	C_m
G_m	total mass flow of gas	$(kg\ CO_2 + CH_4) \cdot h^{-1}$
$G_{m,ca}$	mass flow of carrier gas	$kg\ CH_4 \cdot h^{-1}$
G_{mo}	total molar flow of gas	$(mol\ CO_2 + CH_4) \cdot h^{-1}$
$G_{mo,ca}$	molar flow of carrier gas	$mol\ CH_4 \cdot h^{-1}$
G_v	total volumetric flow of gas	$(Nm^3\ CO_2 + CH_4) \cdot h^{-1}$
$G_{v,ca}$	volumetric flow of carrier gas	$Nm^3\ CH_4 \cdot h^{-1}$
L_m	total mass flow of solvent	$(kg\ CO_2 + DGA + H_2O) \cdot h^{-1}$
$L_{m,ca}$	mass flow of carrier solvent	$(kg\ DGA + H_2O) \cdot h^{-1}$
L_{mo}	total molar flow of solvent	$(mol\ CO_2 + DGA + H_2O) \cdot h^{-1}$
$L_{mo,ca}$	molar flow of carrier solvent	$(mol\ DGA + H_2O) \cdot h^{-1}$
L_v	total volumetric flow of solvent	$(Nm^3\ CO_2 + DGA + H_2O) \cdot h^{-1}$
$L_{v,ca}$	volumetric flow of carrier solvent	$(Nm^3\ DGA + H_2O) \cdot h^{-1}$
x	mole fraction of the component in the liquid phase	$mol\ CO_2 \cdot (mol\ CO_2 + DGA + H_2O)^{-1}$
X	moles of the component in liquid per mole carrier solvent (mole ratio)	$mol\ CO_2 \cdot (mol\ DGA + H_2O)^{-1}$
y	mole fraction of the component in the gas phase	$mol\ CO_2 \cdot (mol\ CO_2 + CH_4)^{-1}$
Y	moles of the component in gas per mole carrier gas (mole ratio)	$mol\ CO_2 \cdot (mol\ CH_4)^{-1}$

The mass balance across the column is given by Equation 5, and the component balance by Equation 6.

$$L_{m,in} + G_{m,in} = L_{m,out} + G_{m,out} \qquad (Eq.\ 5)$$

$$x_{in}L_{mo,in} + y_{in}G_{mo,in} = x_{out}L_{mo,out} + y_{out}G_{m,out} \qquad (Eq.\ 6)$$

In a column, as CO_2 is transferred from one phase into another, the concentration of CO_2 in a phase and the total solvent and gas flow rates change continuously. However, the carrier solvent and carrier gas flow rates do not change. Therefore, the component balance can be rewritten as Equation 7, which is mathematically simpler than Equation 5.

$$G_{mo,ca}(Y_{in} - Y_{out}) = L_{mo,ca}(X_{out} - X_{in}) \qquad (Eq.\ 7)$$

Presenting CO_2 content as moles of CO_2 per mole carrier fluid (*X* or *Y*) offers a mathematical advantage: as the solvent and gas flow through the column, only the numerator in *X* or *Y* changes; the denominator remains constant. The relation between capital *X* and small *x* and capital *Y* and small *y* is shown in Equations 8 and 9.

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$$X = \frac{x}{1-x} \qquad\qquad (Eq.\,8)$$

$$Y = \frac{y}{1-y} \qquad\qquad (Eq.\,9)$$

The component balance across any cross section in the column will have the same form as Equation 7; thus, X and Y at any particular point inside the column are related as shown in Equation 10. Y is a linear function of X, and the segment between the coordinates (X_{in}, Y_{out}) and (X_{out}, Y_{in}) is called the operating line.

$$Y = \left(\frac{Y_{in} - Y_{out}}{X_{out} - X_{in}}\right) X + \left(\frac{Y_{out} X_{out} - Y_{in} X_{in}}{X_{out} - X_{in}}\right) \qquad\qquad (Eq.\,10a)$$

$$Y = \left(\frac{L_{mo,ca}}{G_{mo,ca}}\right) X + \left(\frac{Y_{out} G_{mo,ca} - X_{in} L_{mo,ca}}{G_{mo,ca}}\right) \qquad\qquad (Eq.\,10b)$$

The operating line (Equation 10) can also be formulated in terms of x and y, but then, $y = f(x)$ will not be a linear function, but a concave downward curve. If the concentration of the component that is to be separated is small ($y \leq 0.1$), the gas is termed as "dilute", and $y \approx Y$ and $x \approx X$. Moreover, solvent and gas flow rates can be assumed to remain constant throughout the column: $G_{m,in} = G_{m,out}$ and $L_{m,in} = L_{m,out}$. Thus, for dilute gases, the operating-line equation is reduced to Equation 10c, which is often found in university textbooks. The opposite of a dilute gas is a concentrated gas wherein the concentration of the component that is to be separated is large. For concentrated gases, the previously mentioned assumptions do not apply, and the use of Equation 10c for concentrated gases is erroneous.

$$y = \left(\frac{L_{mo}}{G_{mo}}\right) x + y_{out} - \left(\frac{L_{mo}}{G_{mo}}\right) x_{in} \qquad\qquad (Eq.\,10c)$$

CO_2 content at equilibrium in the gas and liquid phase are mathematically related by an equilibrium curve $Y^* = f(X)$ or $y^* = f(x)$ where the slope of the equilibrium curve is denoted as sl. The equilibrium CO_2 solubility values are denoted by adding the superscript "*" to the symbols y, Y, x and X. The function $y^* = f(x)$ is a line in the region where x approaches 0: here sl is constant and is equal to Henry's constant. The form of the function $y^* = f(x)$ cannot be generically stated for the entire range of x, i.e. between 0 and 1. Nevertheless, $y^* = f(x)$ can be approximated by a line or an exponential function for a smaller range of x. Similarly, $Y^* = f(X)$ can also be approximated.

When designing an absorption plant, the absorber is designed at first, followed by the stripper. The quantity and composition of the feed gas are given, and the composition of the treated gas is specified. Therefore, the parameters $G_{mo,ca}$, Y_{in} and Y_{out} for the absorber are given. Subsequently, the solvent is selected, and the vapour-liquid equilibrium data for the solute-solvent system at the absorption and desorption temperatures is ascertained. Thus $Y^* = f(X)$ is determined for the absorber and the stripper. In the case that no exogenous strip gas is used, the minimum possible solute concentration in the solvent at absorber inlet X_{in} is the equilibrium solute concentration at the reboiler temperature in the stripper.

The graphical method for determining the minimum molar solvent flow rate $L_{mo,ca,min}$ is illustrated with the help of Figure 3.3. With X and Y as axes, the equilibrium curve $Y^* = f(X)$ at the column temperature is plotted (Step 1). Then, the point (X_{in}, Y_{out}) is plotted (Step 2), and it constitutes one end of the operating line. Y_{in} is located on the Y-axis and a horizontal marking line is drawn till the equilibrium curve (Step 3). A line is drawn starting from the point (X_{in}, Y_{out}) till the intersection point of the marking line and the equilibrium curve (Step

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4). The coordinates of this intersection point are (X^*_{out}, Y_{in}). The slope of this line is $L_{mo,ca,min}/G_{mo,ca}$ where $L_{mo,ca,min}$ is the minimum solvent flow rate necessary to treat the feed gas (Equation 11).

$$L_{mo,ca,min} = G_{mo,ca}\left(\frac{Y_{in} - Y_{out}}{x^*_{out} - x_{in}}\right) \hspace{2cm} (Eq.\,11)$$

The ultimate solvent flow rate $L_{mo,ca}$ is typically 1.1 to 3.5 times the minimum solvent flow rate $L_{mo,ca,min.}$
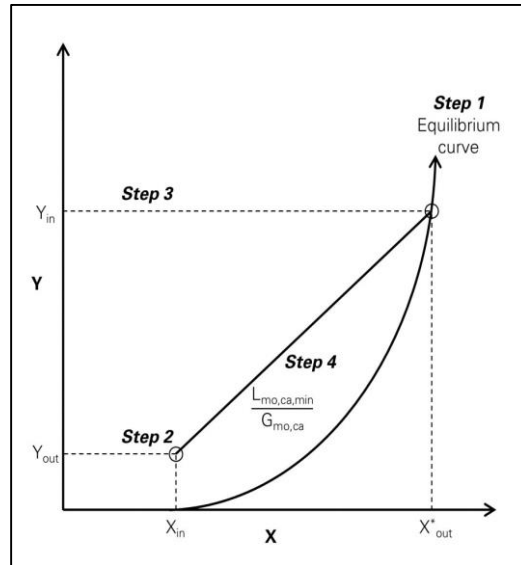

Figure 3.3. Graphical determination of minimum solvent flow rate

In the case of 30% MEA, the equilibrium curve $Y^* = f(X)$ for the solubility of CO_2 in this solution at the column for a temperature equal to 35°C is depicted in Figure 3.4.
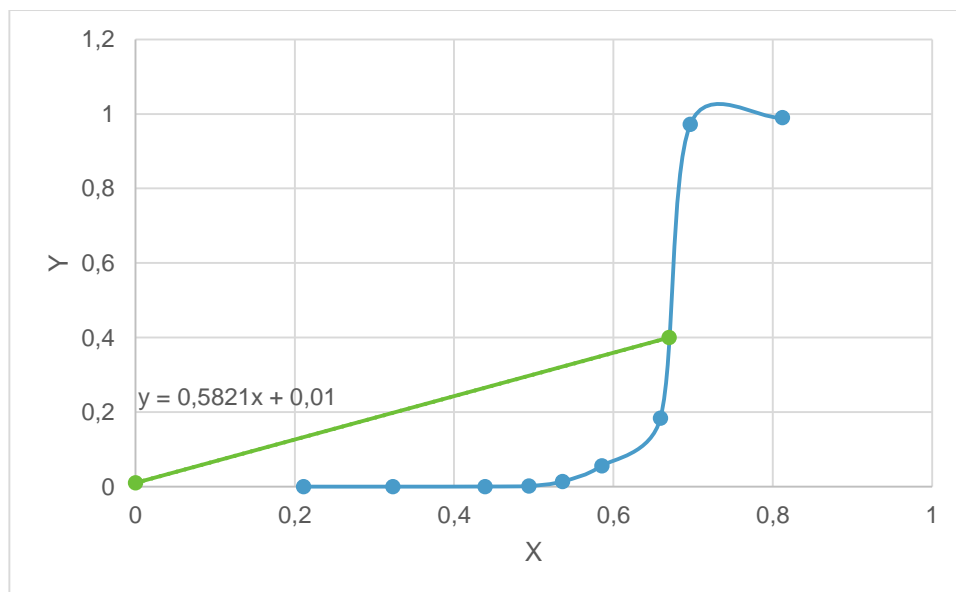

y = 0,5821x + 0,01

Figure 3.4. Equilibrium curve for the solubility of CO₂ in an aqueous solution of 30% MEA at 35°C.

According to Figure 3.4 the slope of the operating line is equal to 0.582. Therefore:

$$\frac{L_{mo,ca,min}}{G_{mo,ca}} = 0.582 \; \frac{mol \; of \; 30\% \; MEA}{mol \; of \; gas} \qquad (Eq \; 12)$$

According to the productivity of the UASB the design volumetric flow of biogas is G_V=30 m³/d= 1.25 m³/h. Making the assumption that the gas consists mainly of methane (through recirculation between the scrubber and gasholder) we can calculate the molar flow of carrier gas $G_{mo,ca}$ through the calculation below:

$$G_{mo,ca} = \frac{\frac{30m^3}{24h}}{0.0224\frac{m^3}{mol \; of \; gas} \times \frac{308K}{273K}} = 49.46 \; \frac{mol \; of \; gas}{h} \qquad (Eq. \; 13)$$

Using equations 12 and 13 we can calculate $L_{mo,ca,min}$:

$$L_{mo,ca,min} = 0.582 \; \frac{mol \; of \; 30\% \; MEA}{mol \; of \; gas} \times 49.46 \frac{mol \; of \; gas}{h} = 28.79 \; \frac{mol \; of \; 30\% \; MEA}{h} \qquad (Eq. \, 14)$$

The ultimate solvent flow rate $L_{mo,ca}$ is equal to:

$$100.765 \; \frac{mol \; of \; 30\% \; MEA}{h}$$

The total volumetric flow of solvent is equal to:

$$L_v = \frac{L_{mo,ca,min} \times MW_{30\%MEA}}{\rho_{30\%MEA}} = \frac{100.765 \; \frac{mol \; of \; 30\% \; MEA}{h} \times 30.934 \; \frac{g}{mol \; of \; 30\% \; MEA}}{1,168\frac{g}{L}} = 2.67 \frac{L}{h}$$

Column diameter

Column diameter d_{COl} depends upon the packing material, the solvent and gas flow rates. d_{COl} is calculated such that the solvent and gas come in sufficient contact with each other in the presence of the packing material. The specific pressure drop $\Delta P/l$ in the packed column is an indicator of the degree of contact between the solvent and gas.

The gas flow rate is represented by the F-factor F_{gas} that indicates the force exerted by the gas in the direction of the gas flow, i.e. upwards (Equation 15 where v_{gas} is the superficial gas velocity, and ρ_{gas} is the gas density).

$$F_{gas} = v_{gas}\sqrt{\rho_{gas}} \qquad (Eq. \, 15)$$

The capacity factor C represents the balance between the upward and the downward forces acting upon a solvent drop (Equation 16 where ρ_{solv} is the solvent density).

$$C = v_{gas}\sqrt{\frac{\rho_{gas}}{\rho_{solv} - \rho_{gas}}} \qquad (Eq. \, 16)$$

Another factor that influences the $\Delta P/l$ is the packing geometry, which is characterized by the packing factor *PF*. The specific pressure drop at flooding $\Delta Pfl/l$ can be calculated using *PF* as per Equation 17, which is an

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empirical correlation (Kister et al., 2007). While using Equation 17, PF must have a unit of ft^{-1}, and $\Delta Pfl/l$ will have a unit of inch H$_2$O per feet packing.

$$\frac{\Delta P_{fl}}{l} = 0.12 PF^{0.7} \qquad\qquad (Eq.\,17)$$

C and PF are consolidated using the term capacity parameter CP as shown in Equation 18 where μ_{solv} is the dynamic viscosity of the solvent, and ρ_{solv} is the solvent density.

$$CP = C \times PF^{0.5}(\frac{\mu_{solv}}{\rho_{solv}})^{0.05} \qquad\qquad (Eq.\,18)$$

For a given solvent and gas flow rate, a higher CP indicates a higher $\Delta Pfl/l$. CP and the flow parameter FP are correlated using constant $\Delta P/l$ curves in a graph called the generalized pressure drop correlation (GPDC) chart (Figure 3.5). When FP is kept constant, specific pressure drop increases with increasing CP.
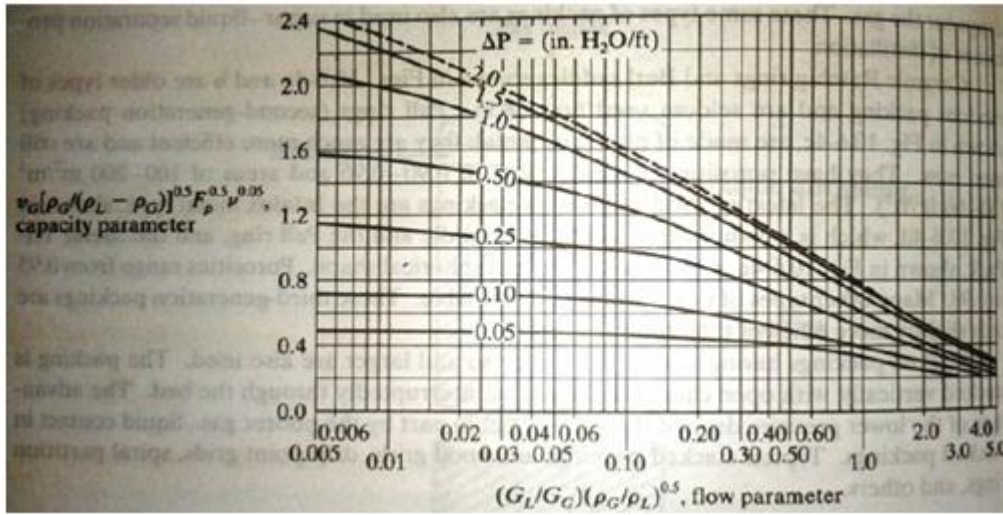

Figure 3.5. GPDC chart

The column diameter d_{col} should be such that it ensures intensive contact between the solvent and gas, but avoids column flooding. Therefore, at the design point or the operating point of the column, the superficial gas velocity $v_{gas,op}$ is selected to be 80 % of the superficial gas velocity at the flooding point $v_{gas,fl}$ (Coker, 2010). The procedure to calculate d_{col} is as follows:

1. Flow parameter FP of the column is calculated as the ratio of the square root of kinetic energy of the solvent and the gas, as per Equation 19 where L_m and G_m are the solvent and gas mass flow rates, respectively, and ρ_{solv} and ρ_{gas} are the solvent and gas densities, respectively.

$$FP = \frac{L_m}{G_m}\sqrt{\frac{\rho_{gas}}{\rho_{solv}}} \qquad\qquad (Eq.\,19)$$

2. The packing factor PF of the packing is characteristic of the packing material used.
3. Pressure drop at flooding $\Delta P_{fl}/l$ is calculated using Equation 17. PF must have a unit of ft^{-1}, and $\Delta P_{fl}/l$ will have a unit of inch H$_2$O per feet packing.
4. In the GPDC chart, a unique point is located with $\Delta Pfl/l$ and FP (abscissa) known. Subsequently, the capacity parameter CP (ordinate) at this point is ascertained.

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5. Using *CP*, the capacity factor *C* is determined by applying Equation 18 where the *PF* value has a unit of ft^{-1}, the dynamic viscosity of the solvent μ_{solv} has a unit of centipoise, and ρ_{solv} has a unit of kg/m^3 (and not lb/ft^3).

6. Using the *C* value, the superficial gas velocity at the flooding point $v_{gas,fl}$ is determined using Equation 16. Solvent and gas density must have a unit of lb/ft^3, and the unit of v_{gas} will be ft/s.

7. The superficial gas velocity at the operating point $v_{gas,op}$ is fixed at 80 % of $v_{gas,fl}$. The unit of $v_{gas,op}$ must be at last converted to the SI unit of m/s.

8. Column diameter d_{col} is then calculated using Equation 20. If v_{gas} and volumetric flow rate of feed gas G_v have SI units (m/s and m3/h, respectively), d_{col} will also have an SI unit, i.e. m.

$$\frac{G_v}{3600}\frac{1}{v_{gas}} = \frac{\pi d_{col}^2}{4} \qquad (Eq.\,20)$$

In order to calculate the total mass flow of gas and solvent G$_m$ and L_m respectively we are using the following equations:

$$G_m = G_v * \rho_{gas} = 1.448\frac{kg\ gas}{h} \qquad (Eq.\,21)$$

$$L_m = L_v * \rho_{solv} = 3.116\frac{kg\ solvent}{h} \qquad (Eq.\,22)$$

Using the Equation 19 we can calculate the FP:
$FP = 0.068$

Using Pall rings made of polypropylene (PP) with diameter 50 mm as packing material, the PF is equal to:
$PF = 0.457\ ft^{-1}$

According to Equation 17 the pressure drop using the calculated values of *FP* and *PF* is equal to:
$$\frac{\Delta P_{fl}}{l} = 0.069\frac{inch\ H_2O}{ft\ packing}$$

Using the GPDC chart of Figure 3.5, the capacity parameter *CP* (ordinate) is equal to 0.6.

Using Equation 18, the capacity factor C, is equal to 1.206.
Using Equation 16, V$_{gas,\,f}$ is equal to 38.429 ft/s. Therefore:
V$_{gas,op}$=0.8V$_{gas,\,fl}$ = 30.743 ft/s= 9.370 m/s.

Finally, using Equation 20, we can calculate the diameter of the column which is equal to 0.69 cm.
It is not technical feasible to construct such a column as the diameter of each pall ring is almost equal to the diameter of the column. As a result, a bubble column reactor with the same packing material will be used instead of a packed absorber with counterflow. For the design of this type of column, experimental results conducted in lab scale scrubbers will be used.

Based on lab scale experiments, in an amine scrubber full of 30% MEA solution where biogas flows from the bottom towards the top almost 60 L of CO_2 can be absorbed by 1 L of fresh 30% MEA. Therefore, assuming that the average percentage of CO_2 in the produced biogas is equal to 40%, almost 150 L of biogas can be treated with 1 L of fresh 30% MEA. For the design of the amine scrubber, we will take in consideration the use of the regenerated amine solution in combination with the highest biogas productivity which is equal to 30 m^3/d during summer. In order to treat the daily produced biogas which is equal to 30.000 L we require:

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$$V_{30\%MEA} = \frac{30000L \; biogas}{100 \; \frac{L \; biogas}{L_{30\%MEA}}} = 300 \; L_{30\% \; MEA} \qquad\qquad (Eq.\,23)$$

In order to perform the regeneration process once a day a scrubber with a total height of 4 m and a diameter of 40 cm will be used for the upgrading of biogas. The height of the packing material will be 1.2 m.

According to the experimental data, using a scrubber having a height of 1 m with a diameter of 3 cm and a volumetric flow rate of 7L/h, which corresponds to a gas velocity of 0.275 cm /sec almost 100% removal of CO_2 takes place. Therefore, the reaction time of CO_2 with the 30% MEA is less than 363 s. Based on Equation 24 and assuming a flow rate of 1.25 m^3/h for the blower, the gas velocity will be equal to 0.276 cm/s,. This provides a reaction time of almost 1449 sec which is more than enough for the reaction of MEA with CO_2 to take place.

$$v = \frac{Q}{\pi * (\frac{d_{col}}{2})^2} \qquad\qquad (Eq.\,24)$$

A sensor for the online measurement of CO_2 will be installed in the line of the upgraded biogas that exits the scrubber, in order to fine tune the flow of the blower. The flow of the blower will adjustable using a special controller. In addition to this, the indication of this sensor will be used in order to estimate the degree of saturation of MEA.

Once saturated, the MEA will be transferred to the stripper. The dimensions of the stripper are identical to the scrubber. The scrubber will be made of Stainless Steel 316. The saturated solution will be transferred to the stripper using a centrifugal pump and at the same time the gas flow to the scrubber will be stopped using an ATEX solenoid valve and turning off the blower. Being in the stripper, regeneration of the saturated 30% MEA solution can be achieved through heating of the solution at 110°C for 2 hours at atmospheric pressure. The regenerated solution can treat up to 300 L of biogas and the amine losses are equal to 10%. Better results could be achieved through regeneration of 30% MEA solution at 130°C and a pressure equal to 2 bars. Techno-economic analysis will be conducted in order to select the best alternative for the regeneration.

In order to maintain the quantity of the 30% MEA solution in the scrubber a special tank made of PP will be installed in the system. In this tank fresh 30% MEA solution will be stored for a short period of time. In the beginning of each cycle, fresh solution of MEA will be transferred from the tank to the scrubber using a peristaltic pump in order to maintain the initial volume of the solution in the scrubber which is equal to 300 L. The loss of the 30% MEA solution in each cycle of regeneration is calculated to be 30 L, therefore in order to have enough fresh solution for 10 cycles of regeneration a tank of 500L will be installed.

Once a day, the upgraded biogas which will be stored in the gasometer, will be compressed by the FUELMAKER FMQ 2 P30. To remove the humidity from the upgraded biogas a silica column will be installed. The compressed biogas will be stored in the Vítkovice Cylinders 280 L. Finally, using a special Refuelling Pipe the compressed biomethane will be transferred to the specially modified vehicle.

3.5. List of operation units – specifications of electro-mechanical equipment

The main operation units with its corresponding P&ID tag and its specifications are presented in this section

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Equipment associated to the biogas from air-tank to scrubber

Blower

–	Brand:	HIBLOW
–	Model:	HRB-100
–	Flow:	7.2 m³/h
–	Material:	STEEL
–	Power:	0.075 kW
–	Velocity:	50 Hz
–	Protection:	ATEX
–	Air temperature	+70°C

Scrubber

–	Volume:	0.283 m³
–	Type:	Bubble Scrubbet
–	Material:	AISI 316
–	Height:	4 m
–	Diameter:	0.3 m
–	Shape:	Cylindric

Peristaltic Pump

–	Brand:	Injecta
–	Model:	NK.FX.250
–	Flow:	15 l/h
–	Tube Material:	Santoprene
–	Power:	3.5 W
–	Velocity:	50 Hz
–	Protection:	IP 65
–	Air temperature	+70°C

Equipment associated to the biogas from scrubber to stripper

Heat exchanger

–	Brand:	vidaXL
–	Model:	90867
–	Tube inlet:	G 1 ½''
–	Tube oulet :	G 1''
–	Power:	28 kW

– Material:	Inox 304

Stripper

– Volume:	0.283 m^3
– Type:	Bubble Scrubber
– Material:	AISI 316
– Height:	4 m
– Diameter:	0.3 m
– Shape:	Cylindric

Electric resistance (boiler)

– Brand:	MICA
– Model:	MICA-700
– Power:	700 W
– Material:	Tube: AISI 316L

Equipment associated to the biogas from stripper to gas burner

Solenoid Valve

– Brand:	Sirai
– Model:	L282D01
– Body material:	brass
– Seals material:	WRAS EPDM
– Connection:	½''
– Homologation:	ATEX

Flame arrester

– Brand:	PROTEGO® BE/AD or similar
– Housing material:	steel
– Internal elements:	Stainless steel
– Connection:	Flanged connection
– Homologation:	ATEX

Biogas burner

– Brand:	Groth
– Model	Model 8391B or similar
– Housing material:	steel
– in flame area material:	Stainless steel

–	Connection:	2'' (DN 50)
–	Homologation:	ATEX

Equipment associated to the biogas from scrubber to CNG unit

Container for silica

–	Total volume:	140 L
–	Silica gel:	200 kg
–	Silica gel volume:	0.090m^3
–	Height:	2 m
–	Diameter:	0.3 m

Biogas compressor

–	Brand:	FUELMAKER FMQ 2 P30
–	Max Filling Pressure:	207 bar (3000 psig) at 20° C
–	Min Inlet Pressure:	0.017 bar (7" w.c.)
–	Max Inlet Pressure:	0.035 bar (14" w.c.)
–	Nominal Flow:	2.2 sm^3 /h at 21°C - 0.017 bar
–	Electrical Supply:	220 Volt AC Monophase, 50/60 Hz
–	Wiring Circuit Capacity:	15 Amp
–	Full Load Amperes:	6.5 Amp
–	Average Consumption:	0.9 kWh
–	Noise:	49 dBa at 5 m
–	Operating Temperature:	From - 40° C to + 45° C

Tanks for CNG

–	Brand:	Vítkovice Cylinders a.s.
–	Housing material:	Steel
–	Outside diameter:	267 mm
–	Water capacity:	75.0 L
–	Working / test pressure:	200/300
–	Weight	77.0 mm
–	Length	1600 mm
–	Capacity	15.0 m^3

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3.6. List of sensors – meters – automation/control strategy

Table 3.5. List of sensors, meters – automation/control strategy

Type of on-line sensor	Process monitored	Point of installation	Parameter(s) monitored	System output
Gas flow meter	Biogas flow from the air-tank	Air-tank	Flow	Pulse
Pressure start module	Pressure of biogas pipes	Pipes before pressure unit	Pressure	Digital output
Gas detector	Upgrading Unit	Upgrading Unit	Detect and monitor levels of toxic gases, explosive gases	Digital output
Temperature sensor	Amine Scrubber	Amine Scrubber	Temperature	Analog output
Temperature sensor	Stripper	Stripper	Temperature	Analog output
Pressure sensor	Biogas compression	Compression Unit	Pressure	Digital output
Temperature sensor	Amine regeneration	Boiler	Temperature	Analog output

Gas flow meter

– Brand:	Sontay
– Model:	MG 4
– Rang of measurement:	0,29 to 144 m^3/d
– Fluid temperature:	0-60 °C
– Analogic output:	4-20 mA
– Operating voltage:	18-30 DC
– Connection:	Threaded connection G 1
– Protection:	IP 67

Pressure start module

– Brand:	SONTAY
– Model:	PL-630-A-0.02
– Adjustment Range :	6 to 20mbar
– Operating voltage:	12-24 Vdc
– Protection:	IP 65

Gas detector

–	Brand:	SENSITRON
–	Model:	SMART3G-D
–	Range of measurement:	%LEL FOR FLAMMABLE
–	Analogic output:	4-20 mA (200Ω)
–	Operating voltage:	12-24 Vdc
–	Protection:	IP 65

3 Temperature sensor

–	Brand:	WIKA
–	Model:	TR10-C
–	Type:	PT100
–	Range of measurement:	-196 ... +600 °C
–	Analogic output:	4-20 mA
–	Protection:	IP 65

Pressure sensor

–	Brand:	STS
–	Model:	ATM.mini
–	Homologation:	ATEX
–	Range of measurement:	0-250 mbar
–	Operating voltage:	18-32 DC
–	Analogical output:	4-20 mA
–	Protection:	IP 68

3.7. Benefits and limitations

The produced biogas is used for power generation. During the utilization of biogas within a combined heat and power (CHP) unit only 35-40% of the energetic content of the gas is converted into electricity. Another 50-55% is transformed into heat and the rest is lost. For the units that not use heat to control the temperature of reactor, this effectively means that 60-65% of the energetic content of the biogas is not utilized. Converting the biogas into biomethane (of gas grid or CNG quality) through upgrading, would facilitate the transportation and commercialisation of over 95% of the energetic content of the biogas.

Within the compressed natural gas (CNG) utilization route, the raw biogas will be upgraded to a methane content of >96%, compressed to 207 bar and stored in racks with gas bottles. The buffered gas (bottles) will be suitable for transportation by truck or ship. For transportation over large distances (>200km), it will be

advised to further reduce the gas volume by converting the gas to (liquefied natural gas) LNG (through liquefaction). In this project the routes between cities at Lesvos Island are less than 200km, so it not necessary to convert the CNG to LNG.

Other advantages of CNG for transport use are:
- Natural gas vehicles have lower maintenance costs than other hydrocarbon-fuel-powered vehicles.
- CNG fuel systems are sealed, preventing fuel losses from spills or evaporation.
- Increased life of lubricating oils, as CNG does not contaminate and dilute the crankcase oil.
- Being a gaseous fuel, CNG mixes easily and evenly in air.
- CNG is less likely to ignite on hot surfaces, since it has a high auto-ignition temperature (540°C), and a narrow range (5-15%) of flammability.
- CNG-powered vehicles are considered to be safer than gasoline-powered vehicles.]

3.8.   Description of operation

A scrubber containing an aqueous solution of 30% MEA will be used for the upgrade of the biogas. A blower will be used for the circulation of the biogas to the amine scrubber. The upgraded biogas, free of CO_2, will be recirculated back to the gasometer. After absorbing CO_2 in the absorber, the MEA solution becomes saturated being unable to absorb more CO_2. The saturated MEA solution is then sent to the desorber where the temperature is raised, resulting in CO_2 stripping from the amine solution (solvent regeneration). The regenerated solution is then returned to the absorber thereby creating a continuous recycling process. The upgraded biogas is then transferred to biogas compressor which is capable of compressing the biogas up to 207 bar in order to be used as fuel in the automotive sector.

The equipment used for the biogas upgrade shall have the necessary safety equipment (safety valves, pressure sensors, leak sensors etc). When gas is to flow to the burner, a signal to the control panel (normally, a contact closure) causes the solenoid to open, providing a stoichiometric air/fuel mixture to the pilot. The igniter begins sparking and continues until the pilot is lit. The flame sensor will signal "flame on" and the sparking will cease. When the biogas arrives at the burner tip, ignition immediately takes place and the burn is continuous until the gas supply is removed. The pilot will continue to be ignited until the signal is received (contact is opened). The pilot start signal may be provided by a pressure switch. When flaring of the gas is required again, the above sequence will be repeated.

3.9.   Safety instructions

The equipment must be exclusively handled by qualified and/or properly trained personnel, which must provide the appropriate personal protective devices (PPD) to prevent the risks associated to the use of any equipment or to the operating environment in which it has been installed. Table 3.3 shows the symbols of the main personal protective devices which must be available during operation and/or maintenance of the system.

In addition to the use of PPD, to avoid any risky conditions for users or damage to the equipment, it is advisable to strictly follow the warnings and behavioural rules detailed in the equipment datasheets, together with the following indications:

1. CNG safety signage should be visible at all applicable locations.
2. Natural gas rated fire extinguishers should be accessible and visible throughout all servicing and fuelling areas. Be sure all fire extinguishers are charged and up to date.

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3. Areas designated for CNG fuelling systems must have adequate lighting.
4. Search for leaks using only certified leak detecting solutions and equipment. Any other product or solutions are unacceptable.
5. Use tools that are in good working order with proper calibration.
6. Wear appropriate attire and personal protective equipment (PPE) while servicing or maintaining any CNG system. Staff working in areas at high risk of potentially explosive atmospheres forming (in accordance with the ELOT EN 60079 standard) and staff handling any odoriser must have personal protective equipment (PPE) in accordance with the relevant European and Greek Legislation (Regulation (EU) No 2016/425 and Ministerial Decision No. Δ3/A/20701/13-11-2006 (Government Gazette 1712/B/2006)).

Table 3.3 Personal protective devices which must be available for the Biogas Upgrade Systems

	Obligation to use flame resistant clothing significantly reduces burn injuries which can save lives in the event of an accident.
	Obligation to use respiratory protection devices (masks) in presence of harmful vapours or gases.
	Obligation to use protection gloves for chemicals or electricity.
	Obligation to use head protection devices (hard hat) if interventions are required within the perimeter of the machine.
	Obligation to use devices to prevent accidental falls (ropes), especially for operations of assembling, installation and maintenance at height.
	Obligation to use eye protection devices (goggles) if there is a risk of chemicals or process liquids splashes.

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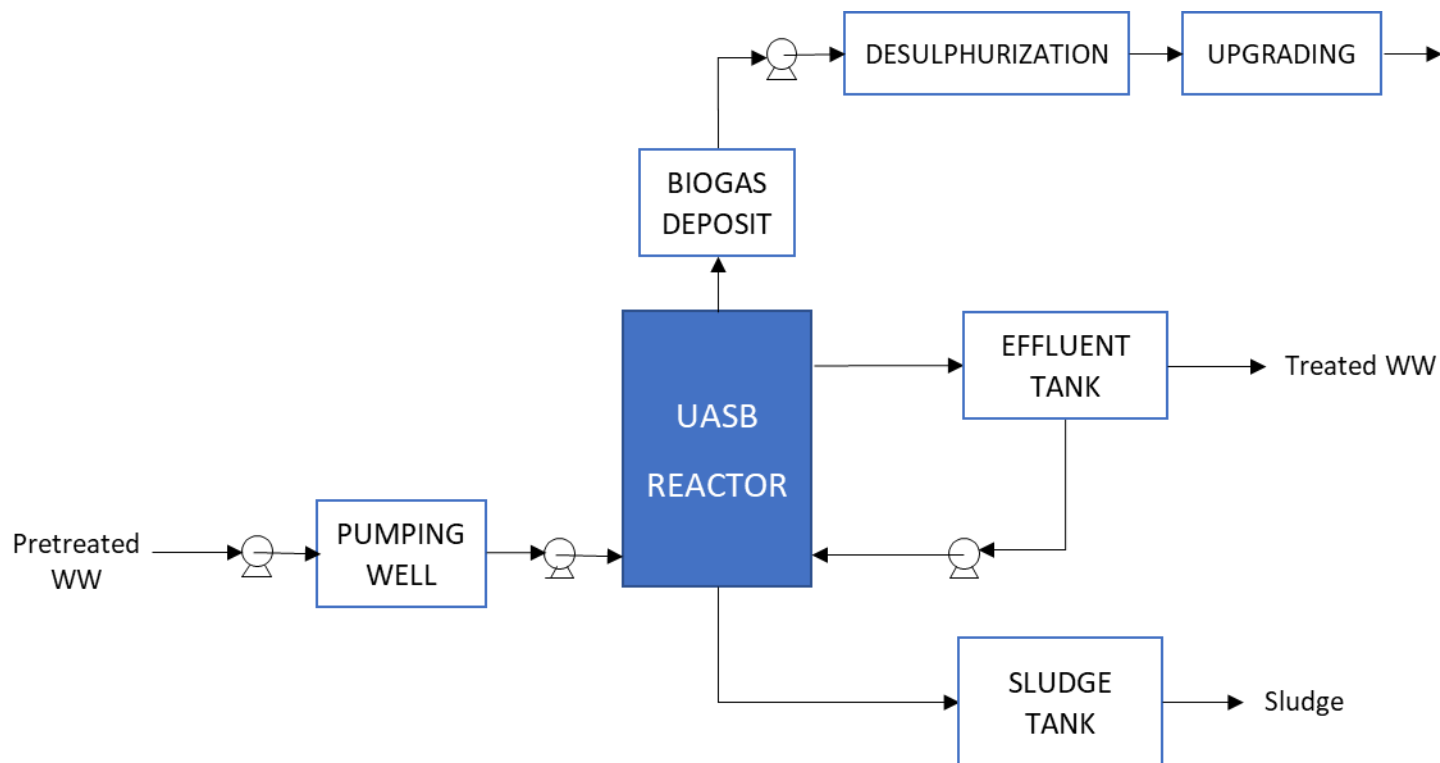van Lier, J. B.; Vashi, A.; van Der Lubbe, J. and Heffernan, B., 2010. *Anaerobic Sewage Treatment using UASB Reactors: Engineering and Operational Aspects*. Environmental Anaerobic Technology. Pp. 59-89.

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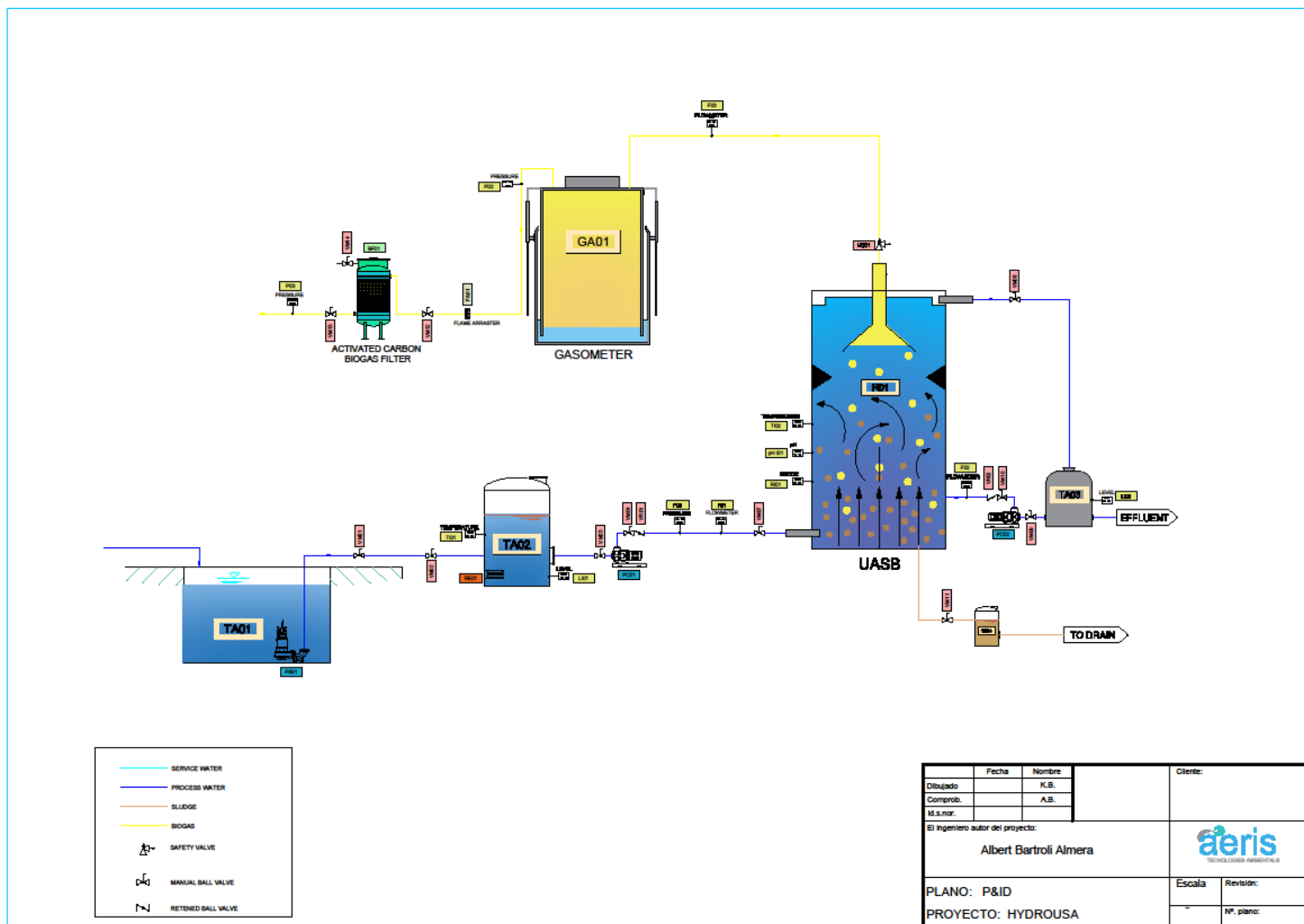under Grant Agreement No 776643

5. ANNEX

The following drawings are reported:

- **Drawing n° 1**: Flow chart of the process for the domestic wastewater treatment of HYDRO1
- **Drawing n° 2**: Piping and Instrumentation Diagram of the installation for the domestic wastewater treatment of HYDRO1
- **Drawing n° 3**: Drawings of the UASB reactor designed for the HYDRO1
- **Drawing n° 4**: Prototype of the UASB reactor designed for the HYDRO1
- **Drawing n° 5**: Piping and Instrumentation Diagram of the Biogas Upgrade Unit
- **Drawing n° 6**: Drawings and Prototype of the Scrubber Unit
- **Drawing n° 7**: Layout of the installation for the domestic wastewater treatment of HYDRO1
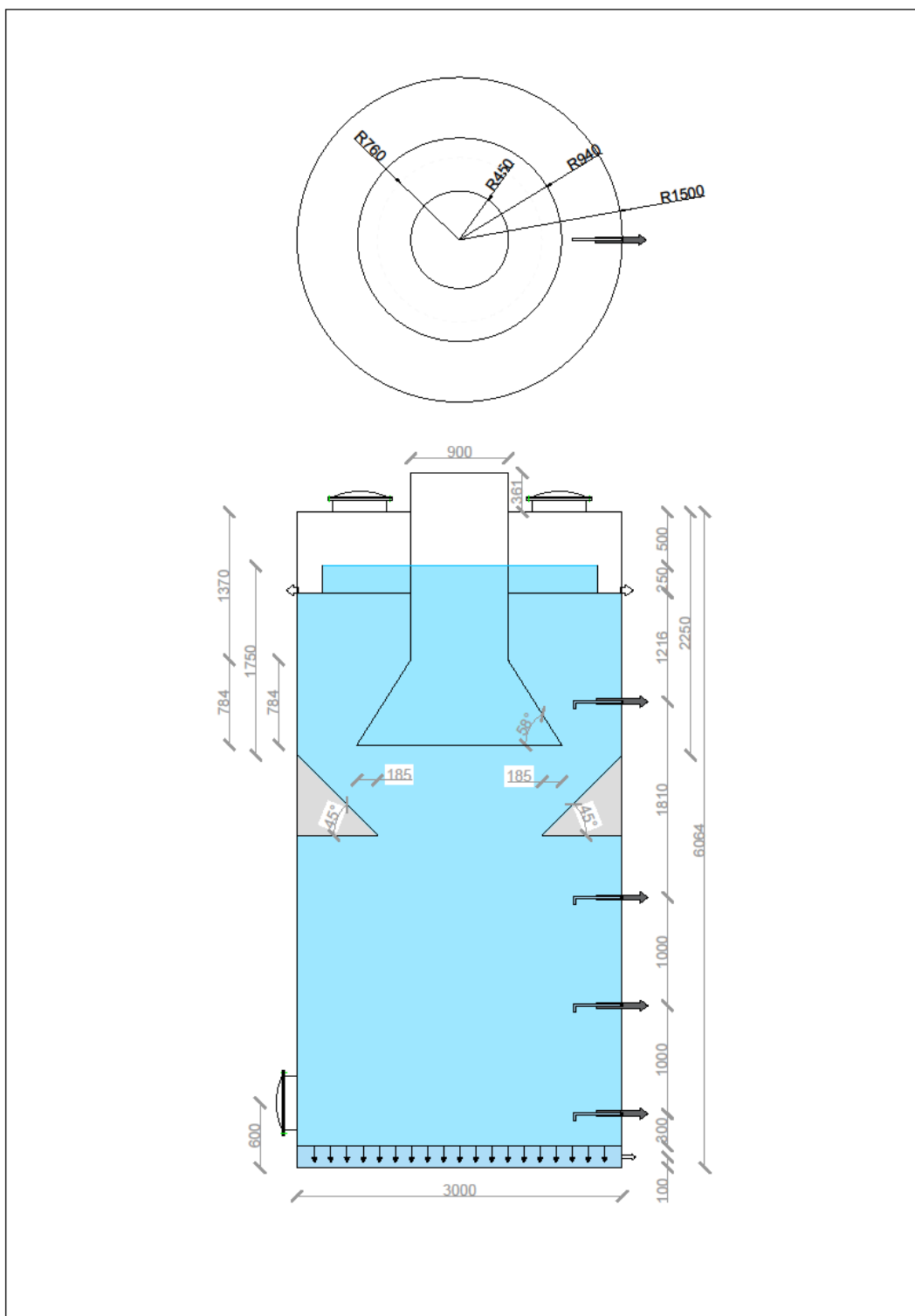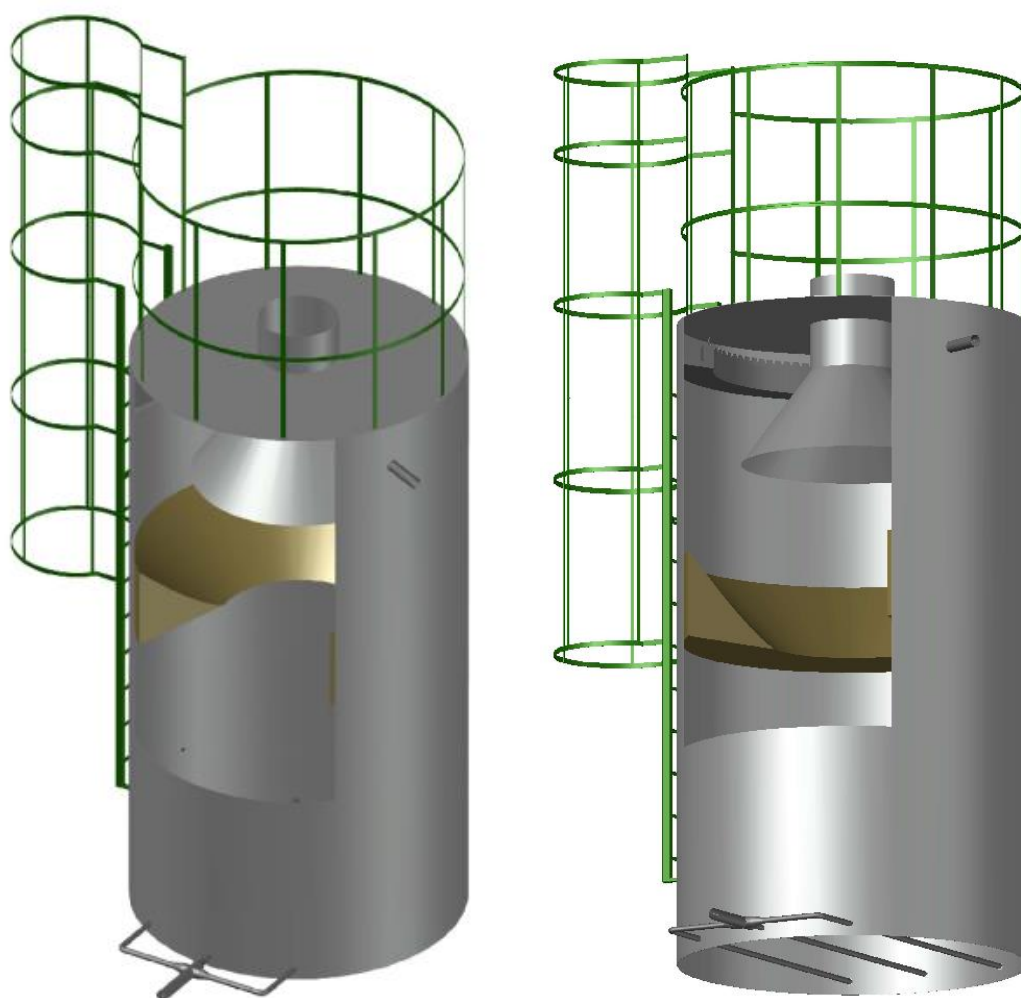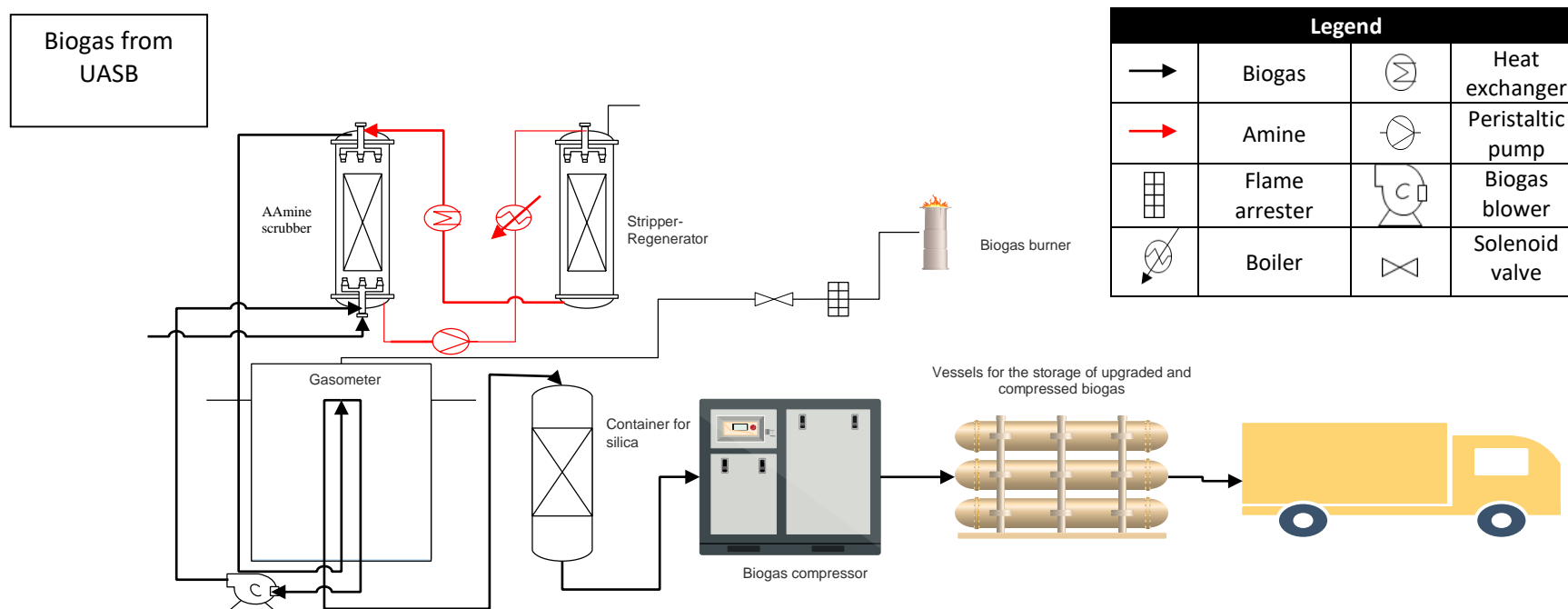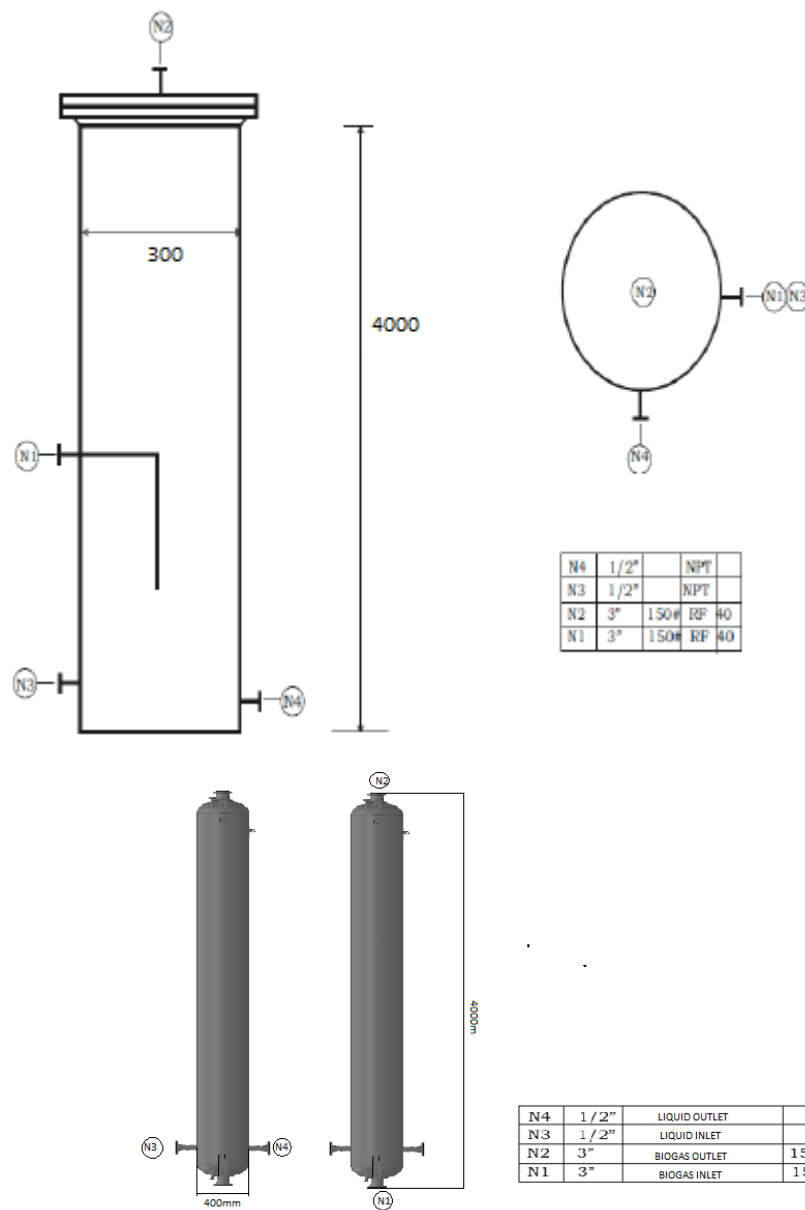
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Drawing n° 1: Flow chart of the process for the domestic wastewater treatment of HYDRO1

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Drawing n° 2: **Piping and Instrumentation Diagram of the installation for the domestic wastewater treatment of HYDRO1**

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Drawing n° 3: Drawings of the UASB reactor designed for the HYDRO1

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Drawing n° 4: Prototype of the UASB reactor designed for the HYDRO1

Biogas from UASB

Legend			
→	Biogas	⊵ (heat exchanger symbol)	Heat exchanger
→	Amine	(peristaltic pump symbol)	Peristaltic pump
(flame arrester symbol)	Flame arrester	(blower symbol)	Biogas blower
(boiler symbol)	Boiler	⋈	Solenoid valve

AAmine scrubber

Stripper-Regenerator

Biogas burner

Gasometer

Container for silica

Biogas compressor

Vessels for the storage of upgraded and compressed biogas

Drawing n° 5: Piping and Instrumentation Diagram of the Biogas Upgrade Unit

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N4	1/2"		NPT	
N3	1/2"		NPT	
N2	3"	150#	RF	40
N1	3"	150#	RF	40

N4	1/2"	LIQUID OUTLET		NPT	
N3	1/2"	LIQUID INLET		NPT	
N2	3"	BIOGAS OUTLET	150#	RF	40
N1	3"	BIOGAS INLET	150#	RF	40

Drawing n° 6: Drawings and Prototype of the Scrubber Unit

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Drawing n° 7: Layout of the installation for the domestic wastewater treatment of HYDRO1