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Feasibility study for valorization of organic waste through anaerobic digestion in a rural municipality of Madagascar

Master thesis

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Abstract

Anaerobic digestion offers possibility to produce renewable energy, reducing greenhouse gases emissions and deforestation by replacing wood cooking fuels with biogas. It is also a way to treat organic waste and manure and to produce a good bio fertilizer. Given all these advantages, implementation of "low tech" AD plants in developing countries should be widespread. In Madagascar, some projects have been set up for 15 years. However, compare to AD potential, the way to generalisation is still long
AD could be a partial solution to problems the country is facing as deforestation, SWM, losses in soils fertility, total dependency from the international fuel market, all these factors contributing to poverty.

We have been working in Ampefy, a rural Municipality in the centre of the Island to test the feasibility of valorisation of Organic Municipal Waste by AD. Simultaneously, an experimental protocol for basic research on AD with 2 floating cover 8m^3 digesters have been set up and a case study on a 4 plants facility belonging to a NGO in the same village has been carried out. Finally, a more general reflection on AD for rural areas of Madagascar was undertaken.
Valorisation of OMSW for small municipalities is technically feasible in every village. Limiting aspects for the success of a project are institutional and financial. These constraints have to be studied on a case-by-case basis to find suitable approaches for each municipality. In the studied municipality, the presence of many local associations, the motivation of hotelkeepers and an existing basis of MSWM were the main assets for implementation of an AD project.
Experimentation protocol was successfully implemented. Experiment has been done with kitchen waste to test the protocol. The difference of productivity in function of particles size loaded has been tested. Productivity, expressed as weight of kitchen waste necessary to produce 1m^3 of biogas, was 1.5 higher with particle of less than 7cm compare to all size particles. The facility is now ready for further researches that could be conducted by Malagasy students.
Experience on AD implementation for rural households shows that if the idea is theoretically interesting for the poorest, in practice, subsidized AD facilities often leads to abandon of the system. More criteria such as technical services availability, waste quantity and transport should be considered. It seems more promising to start with AD promotion for more structured entities like municipalities, hotels, schools or big farms... Then, once the technology is well known in such structures, step by step, implementation will become easier for rural households.

Abbreviations:

AD	Anaerobic digestion
ADEME	Agence de l'Environnement et de la Maîtrise de l'Energie
Ar	Ariary, local money
A/TIC	ratio Volatil Fatty Acid/Total Inorganic Carbon
BMGF	Bill and Melinda Gates Foundation
BMP	Biological Methane Potential
CSB II	Centre de Santé de Base niveau II
CNRIT	Centre National de Recherche et d'Innovations Techniques
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
OFMSW	Organic Fraction of Municipal Solid Waste
SWM	Solid Waste Management
TS	Total Solids
VFA	Volatil Fatty Acid
VS	Volatil Solids

Indication: 1US dollar ≈ 3215 Ariary

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I. Introduction

1. Rationale

In Madagascar, the situation of MSW is critical as there are few initiatives to solve the problem and efforts are concentrated mostly in urban centres. In rural municipalities, the organic fraction in waste is superior to 50% (Hoornweg et Bhada-Tata 2012). If this fraction is recycled, half of the waste is treated. Moreover, the organic fraction buried in dumpsite causes greenhouse gases emissions, produces polluting lixivia released in soils and water, odours and sanitations problems (Sandec 2016). The last argument to treat OMW is the technical feasibility. Recycling of organic waste is easy and accessible compare to the recycling of other fractions as plastic or paper.

Anaerobic digestion offers possibilities to treat organic waste and to generate a value from it: biogas and digestate. In Madagascar, gas is very expensive so very few people can afford cooking with gas. The NGOs PATMAD and CEAS own a drying unit for fruits in the municipality of Ampéfy. The drying for exportations is achieved with gas, leading to high production costs. This is the reason why 4 AD plants were built in 2012. However, plants were not used because of supply problems: it was not possible to buy cow manure at reasonable price to farmers as they use it for their fields. However, the potential of this facility is big. Thus, the NGOs wanted to find solutions to this supply problem.

Moreover, the CEAS is promoting renewable energies and technical innovations to small farmers and local communities and the NGO TIM-SFV wanted to approach the question of waste in rural municipalities. That is why they did a partnership to propose this project, combining AD in rural municipality, experimentation with organic waste to find a new supply strategy for the drying unit and reflexion on AD for rural areas.

2. Framework

This study is the result of a 6 months Master project. The project was proposed in partnership with 3 associations.

- CEAS (*Centre Ecologique Albert Schweitzer*), a Swiss association which works mainly in the area of promoting renewable energies, agro transformation and sanitation. The idea is to provide technical innovations and knowledge to small farmers and collaborators to be independents. They also support local communities on sanitations and agro transformation projects. Countries of action are Senegal, Burkina Faso and Madagascar.

- Tim-SFV (*Tiako-i-Madagasikara Suisse et France Voisine)*, a Swiss association which promote the development of Madagascar in the field of public health, education, energy and environment.

- PATMAD (*Programme d'Appui Technique aux producteurs*), a Malagasy association which works with small farmers, giving technical and material support to promote their products. In this context they also promote renewable energies.

3. Objectives of the work

The work was separated in 4 main objectives.

1. Development of an experimental set up on floating cover digesters to test productivity of biogas in function of feedstock. Establish a protocol of use and simple experimentations for the facility. Test the protocol by making experimentations.

2. Assessment of the potential of an existing AD facility to produce biogas as fuel for a drying unit and proposition of a supply strategy in organic waste for the AD plants in order to reduce gas costs during the drying process.

3. Feasibility study for the valorisation of the organic waste fraction through anaerobic digestion in a rural municipality of Madagascar

4. Reflection on the relevance of biogas as fuel in rural areas in Madagascar

4. Background

a) Demographical and economic situation

Madagascar is an island with 23.6 millions of inhabitants. Since 1970, population was multiplied by 4 and will reach 55 millions of people in 2050 (World Bank 2016) . It is "classified" by the international authorities as "low income country or developing country" as 90 % of the population is living with less than 1.25 US per day (Worldbank 2013). The country is facing many political and economical problems. With the important demographic increase of 2.78 %/year [3] and the rapid urbanisation all the problems will be intensified. That is why the preoccupation for sustainable development is a priority.

b) Wood as energy and solid waste management in Madagascar

On the island, wood is the traditional, cheapest and most used source of energy (wood or charcoal). It represents 92% of the overall energy consumption (Abdallah et Randriambola, 2012). It is estimated that each family consume per day around 1-2kg of charcoal or 7kg of wood that they collect in their surroundings[4].

Then deforestation is a main issue. On the 9 220 040 ha of natural forest estimated in 2010, around 36 000ha are disappearing every year (Office National de l'Environnement Malgache 2013) , bringing a range of related problems as erosion, diminution of biodiversity -one of the biggest wealth of the island- diminution of soils fertility, absence of wood as raw material to build houses, pirogues... Moreover, cooking inside the house with charcoal or wood has become a public health concern as it provokes respiratory problems. It has been estimated that this practice is responsible for 12 000 deaths each year, mostly for children under 5 years(INSTAT 2016).

In the future, the country will have to provide alternatives to wood fuel as the resource will not be sufficient compare to the need (Abdallah et Randriambola, 2012). Ideally, the island would also like to reduce its dependency to fossil fuel because of the concerns in the security of supply and the unpredictable price fluctuations. These elements are to consider in the balance to promote sustainable resources.

Another problem that the country will have to face, due to the increase of urban population (Worldbank 2016) is the solid waste management. Until today management of waste is critical as there is no national plan for SWM, investments are low and citizens are not sensitized at all to this question. SWM will have to become a priority for the government in order to avoid serious environmental and health problems. Solutions exists to treat waste, moreover, at least 52% of waste generated are organic and biodegradable(Hoornweg et Bhada-Tata 2012; Ministère de l'Environnement et des Forêts 2012), and then "easy" to recycle.

c) Opportunity for AD in Madagascar

In this context, anaerobic digestion is a unique opportunity to treat solid waste in Madagascar. It offers possibilities to fight against deforestation, improve waste management, avoid dependency to the global market of energy (gas) and reduce greenhouse gas emissions.

The focus in this work will be on anaerobic digestion in "semi urban" and rural area. Often, plan of SWM are done for big cities (Houllier 2016; Ministère de l'Environnement et des Forêts 2012; représentant AFD 2016) because more waste are generated there, population is dense, and there is no space to throw it hazardously. The pollution is then directly visible and diseases can spread fast. However, it is also important to think of the waste management in smaller urban area. Madagascar as an incredible environment with around 90% of endemic species (WWF 2016), it has to be preserved and the inhabitants too.
That is why adequate waste management strategies on small scale would be interesting. It could be a solution to treat waste but also for small communities to produce energy and products as fertilizers from organic waste. Some AD systems are considered as "low tech". In the context of Madagascar, this kind of facilities is suitable as they are cheap, easy to use, maintenance is low and they are feasible with local material and skills.

d) State of the art for AD in Madagascar

Most of the initiatives for AD plants have been undertaken in the last 15 years(Ravoavison et Hofs 2008). Most of them are small and designed for a family.
All the plants in the country can be considered as "low tech" and small facilities. They are all mesophilic AD and do not exceed 35m^3. The only exception is the new digester of Loowatt, in collaboration with the BMGF, which is equipped for precise measurements to perform researches on AD (Segretain 2016).
Following installations were visited for the project:

- $8m^3$ floating cover digester for a family. Asense, the company selling this “kit” sold 100 unities in 10 years in the island. They do not know how many are still in service, but it probably do not exceed 60%(Krieger 2016).
  Most of the users are using pig manure or cow dung as inputs. Some of them add a bit of kitchen waste. Very few are using human faeces as inputs.

- The National Research Centre for Innovation and Technique (CNRIT) is doing experimental work on AD. They also work in collaboration with organisations for the implementation of AD plants. They have to face many problems as social acceptance, abandon of the plant for unknown reasons... Thus, many projects are not working ideally (CNRIT 2016).

- $30m^3$ fixed dome digester in Antananarivo for the treatment of sewage sludge[9]. It is a project of the Agence Française du Développement in collaboration with the CNRIT. The facility produces electricity for the site, cooking fuel for the worker on site and compost (after post treatment). The plant is actually underused because of management problems (représentant AFD 2016).

- $15m^3$ floated dome digester for market waste in Toliara. This is a project from the NGO Welt Hunger Hilfe. The AD plant has been built to sensitize population to the worth of organic waste (Houllier 2016; Madagate 2016).

- 2 digesters in Antananarivo. They are projects of the NGO Loowatt. One of the digester is a container of around $40m^3$. It produces electricity and the thermal losses around the generator are used to sterilize the feedstock. A co-digestion is carried out, mixing human faeces either with water hyacinth or kitchen waste. Inputs are shredded before loading. Digestate is used to produce compost(Segretain 2016).

5. Overview on anaerobic digestion

a) What is anaerobic digestion?

It is the degradation and stabilisation of organic compounds by microorganisms in absence of oxygen. This leads to gas production and liberation of the rest of the digestion, the digestate. Gas is mainly methane and carbon dioxide, this mixture is called « biogas »and is energy rich. It can be use as cooking gas or to produce electricity. The digestate is a very nutritious matter appreciates as fertilizer. AD is a natural process happening in stomach of ruminants for example. The technology of AD consist in applying this process in engineered plants called digesters to process organic matter and produce gas(Eawag 2014).

b) Steps of digestion

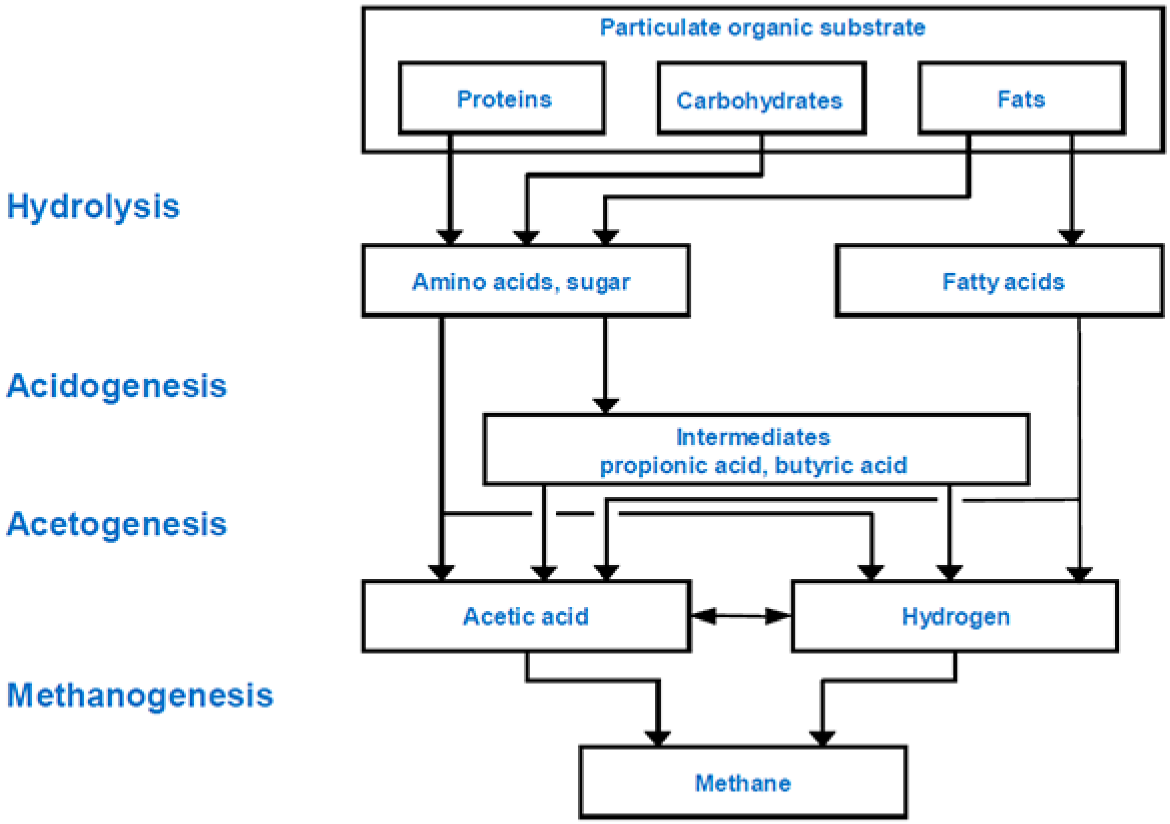

Figure 1: the 4 biochemical steps of AD, *source www.wtert.eu*

The AD process is achieved in 4 steps. Each step is carried out by one sort of bacteria. The first step is often the rate limiting one. It is the **hydrolysis**; organic molecules are hydrolyzed to small polymers or monomers. Depending of their original nature, it will be hydrolyzed into different compounds. This step is particularly long for lignin rich compounds. That is why it is recommended not to use this kind of substrate. (WtERT 2016)

Then, the small organic molecules are converted into intermediates as alcohols, acids, acetate, hydrogen and carbon dioxide. It is the **acidogenesis.** Later, during the **acetogenesis,** all the intermediates are transformed in acetic acid, hydrogen and carbon dioxide. The last step is the **methanogenesis**. Methane synthesis is achieved by 2 types of bacteria using different initial products (either H_2 and CO_2 or acetic acid). (Eawag 2014; Schnurer et Jarvis 2010)

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c) Benefits and shortcomings

<u>Benefits of biogas technology</u>

- Sustainable source of energy as it has a carbon neutral cycle: carbon emitted from burning is absorbs by plants that could be used again as feedstock to produce gas.

- Can reduce deforestation by replacing charcoal or wood fuel.
- Clear combustion as wood fire : reduces risk of respiratory diseases
- Treat the organic fraction of waste; in Madagascar it represents at least the half of the solid waste. It is a solution to reduce the volume of waste in landfills or dumping site. It also avoids methane emission due to anaerobic degradation in dumping site and soil and water pollution due to lixivia(Sandec 2016).
- Release a very nutritious digestate
- Possibility to treat faecal sludge with a low budget on a small area(GRET 2016)
- Can be build with local material and competences
- AD destroys all weed seeds, thus reducing the need for herbicides when used as compost/fertilizer (Ngumah et al. 2013)

Shortcomings

- “low tech” AD plants are limited in size. It is a decentralized solution and cannot be used to treat all wastes of a city for example. It can be complementary to composting in case of big quantities of waste.
- Despite the facility of the process and system, it requires some basics skills to be able to solve problems and maintain the plant.
- Digestate has to be use with caution as is can be very nitrogen-rich(Eawag 2014; Smit et Rigby 2011).

d) Type of digesters for small scale AD

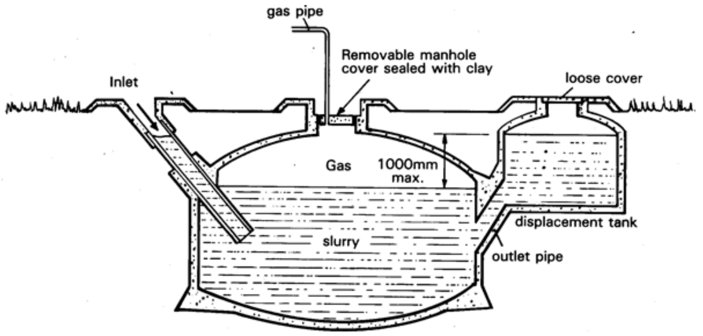

Figure 2: fixed dome digester, *source FAO corporate document history : http://www.fao.org/docrep/t0541e/T0541E0E.GIF*

Fixed dome digester

Digester known as the “Chinese model”.

The all plant is made with “rigid” materials, there is no removable parts. It can be entirely made with local material.

The displacement tank allows a change of level of liquid, in function of biogas quantity (see the scheme for details). It is usually built underground but can be built above too.

Tubular digester

It is a simple long shaped plastic bag with inlet and outlet.

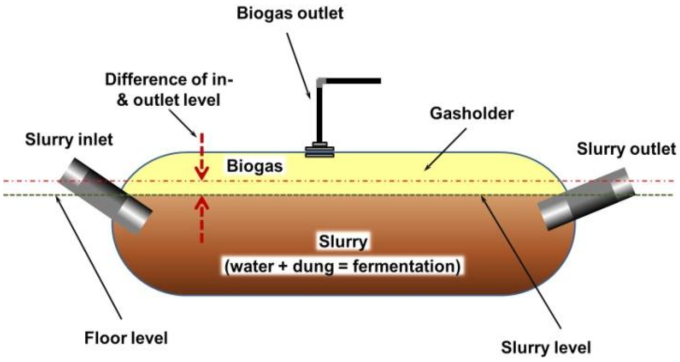

Figure 3: Tubular digester, *source: energypedia, https://energypedia.info/wiki/Experience_with_Polyethylene_Biogas_Digester_(PBD)*

Floated dome digester

Known as “the Indian model”. Easy to build, easy maintenance. Size very variable so the system is very flexible. Weight are added on top to have a constant pressure.

Floating cover digester

this model is a simplification of the floated dome digester. (for plan, see figure 5 section III). The dome is a “plastic balloon”. Air tightness is ensured by the level of water, coming above the border of the tarp.

(Eawag 2014; Energypedia 2016)

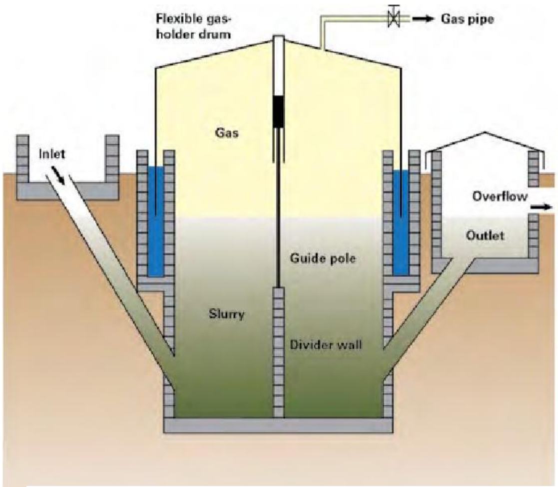

Figure 4: : floating drum digester, *source: Estoppey 2010*

Tableau 1: comparison of the 4 type of "low tech" AD plants

Type of digester	Main advantages	Main shortcomings
Fixed dome	-Long lifespan if well done -Save space -Avoid big temperature variations -No corrosion problem due to H_2S -Relatively low cost compare to lifespan	-Require skilled mason -No vision of gas produced -Difficult draining/maintenance in case of problem
Floated dome	-Easy to build -Vision of gas produced and constant pressure of gas -Easy access to digester	-Problems of corrosion of the dome due to H_2S, maintenance necessary (painting) -Steel or glass fiber drum is expensive -
Floating cover, “balloon plant”	-Cheap -Vision of gas produced -Easy access to digester -Possibility to mix inside the digester slightly with a stick	-Compressor necessary to have constantly a sufficient pressure -Important loses of gas on the borders of the tarp -Short life span of the tarp
Tubular digester	-Very simple to build -Very cheap -Easy maintenance -Possible to transport it	-Very fragile -No local material -No constant pressure

Pre and post treatment of biogas and digestate, possible uses of biogas, use/interest of digestate will be covered in section III

e) Storage

Biogas has a low energy density. 1m^3 biogas contains the equivalent of 0.6 to 0.7 litres of fuel oil. For this reason, compression can be interesting. However, compression is energy consuming and requires equipment(Eawag 2014). 3 kind of storage can be done:

- **Low pressure storage**, either on the top of the digester (floated dome for example) or in a separate tank/bag. To store a big amount of gas, the dome can be insufficient. Bag are a solution, moreover, it could be built in the country but bags are fragile, UV and temperature sensitive and very voluminous.
- **Medium pressure system** (around from 5 to 20 bars) are interesting as only 3 to 4% of the energy of the biogas is necessary to compress it and it can be achieved with a compressor.
- **High-pressure systems** are not suitable in our case as 1/3 of energy from the gas goes into compression energy so the production rate should be very high.

Storage has to be considered if too much gas is produced for the daily use. Nevertheless, the return on investment period can be long so the idea of distributing biogas in the surroundings should also be considered.

II. Development of an experimental set up on AD floating cover digesters

The purpose of the work was **to establish a protocol and build a set up to generate data on AD** in a rural area in Madagascar, especially with kitchen waste because very few experiments are done there and it is difficult to find basic information as gas yields for quantities of different input. The experiment done to test the protocol allows to have some data but it was a test so it is not entirely reproducible and results are not all representatives.

1. Parameters to test

➢ Feedstock:

For the experiment, it was considered to test:

- Different type of inputs: kitchen waste – cow dung – pig manure – water hyacinth
- Different input size: shredded/grinded inputs in piece of less than 3cm / "small"(up to 7cm of diameter")particles / not mechanically pre-treated particles (all size)
- Different solid to water ratios

Only 2 AD plants were usable. As a consequence, only 1 parameter could be tested. At the beginning, the idea was to compare water hyacinth with kitchen waste.

A test was done with water hyacinth (as there is plenty in the surroundings) cut in pieces of less than 7cm. However, fresh water hyacinth blocked the entrance. Moreover, it has been seen that they do not decompose well in the digester as they float. It is necessary to grind them or to dry or to do a pre fermentation in order to reach a good decomposition(Oumarou, Millogo, et Kenfack 2016; Houllier 2016). As it requires a pre treatment and as it was economically not sustainable to pay for bags of water hyacinths, **it was decided to focus on kitchen waste as feedstock.**
For the size of particle, as no grinder was available, **the comparison was done between "selected size (less than 7cm)" and "all size" of kitchen waste**. The **solid:water ratio was always 1:2**. This ratio was chosen, as it was not possible to measure TS and VS. It assumes that kitchen waste have a TS between 5 and 20 % of raw waste(Eawag 2014) and a VS content of about 80 – 90% of TS. 1:2 as ratio ensure a sufficient quantity of water in the process, a simple loading process and avoid a loading rate of VS superior to 2kg VS/day/m^3 with HRT of 30 days minimum(House 2006).

➢ Gas quantity in function of inputs

➢ Gas quality: proportion of CH_4 to CO_2

As biogas is mainly constituted of methane (from 50 to 80%) (House 2006)and carbon dioxide, this gas quality was tested with a basic method using NaOH.

- Digestate quality: C:N ratio
- Stability of the process: A/TIC ratio

2. Material and method

a) Description of the AD facility:

4 AD plants of 8m^3 : 4.5m^3 for liquid phase, 3.5m^3 for the gas storage

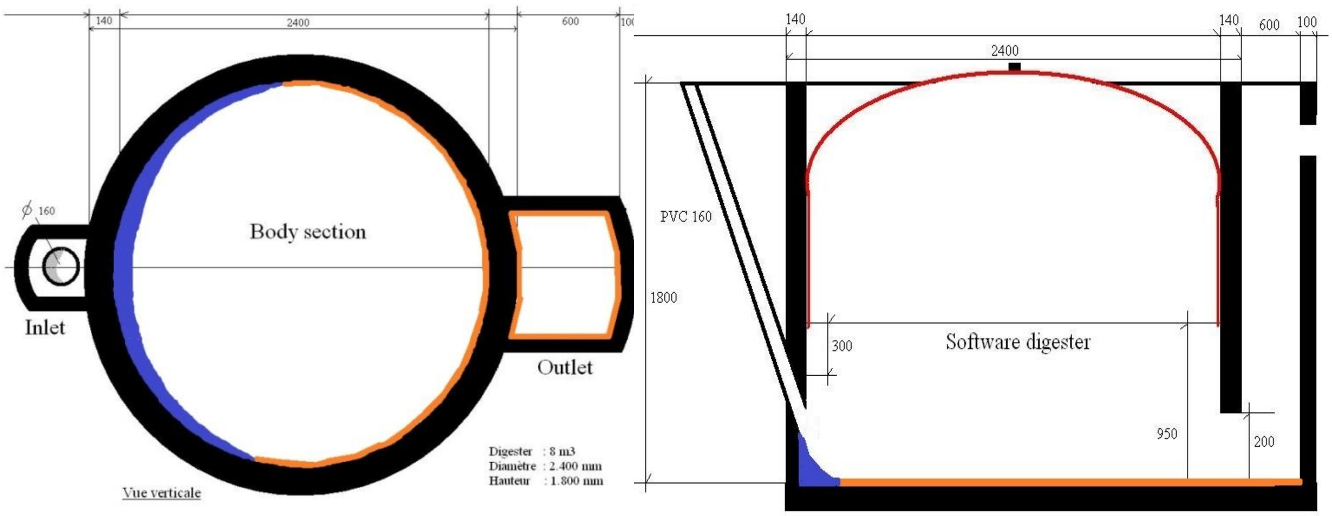

Figure 5: plan of the floating cover digester. In blue and orange on the plan, it is a proposition to repair and improve the tank. Proposed to the NGO *source: Provider documentation (Asense)*

Model: “floating cover digester”, a resistant tarp is fixed above the digester. Water goes up on the tarp for air tightness to oxygen (see picture 2). Currently, 2 digesters were out of order because of leaks.

b) Feedstock and biogas measurements

- For gas production measurements in function of inputs:

  - An old balance (max 300kg) to weight each seal of input
  - Seal of known volume for water
  - Gas meter Itron Gallus G4 (min flow rate 0.04m^3/h, max 6m^3/h)
  - Compressor to ensure a constant pressure for the flame (as the pressure in the dome is not always sufficient to reach the kitchen stove.
  - pH Paper
  - Thermometer (fixed on a tube to be able to insert it between the wall and the tarp and measure the temperature inside the tank).

- For characterisation of the feedstock, measurements of % of moisture content were done as no mixer and good oven at 105°C was available to do a TS quantification, (See appendix 3 for procedure)(Voegeli et al. 2009). The TS % is the result of the humid weight minus the moisture content.
  Measurements of VS were not possible as no and muffle furnace was available.

- For gas quality measurement: the ratio CO_2:CH_4 was measured (see appendix 3 for detailed method).

c) Effluent/digestate analysis:

- For A/TIC experiment: Quantification of inorganic carbon and VFA were done following the Kapp method (Estoppey 2010; Buchauer 1998). See appendix 3 for detailed method.

- The Total Kjedahl experiment was carried out in the laboratory for environmental analysis in Antananarivo. Basic Kjedahl procedure was followed.

- The C:N ratio was also done at EPFL with a TOC analyser Shimadzu TOC-V.

Calculations to estimate maximum capacity of a digester was done as follow:
The maximum daily load was calculated in function of the size of the plant and of the HRT wished (Eawag 2014)

In our case: volume of the plant: 4.5m^3 for solids so V = 4500L

Daily inputs (solids + water) =$\frac{V(Litres)}{HRT(days)} = MaximalDailyLoading(MDL)(^{L}/_{jour})$

The 1 : 2 ratio for Solid to water was always used to avoid overloading of more than 2kg VS/day/m^3. To estimate the TS and VS contents, results of the experiment for TS plus literature values were used.

Remark: *For a MDL of 150L, it was thus approximated than waste has the same density than water to facilitate calculations. The result in this case is 100L of water for 50kg of organic waste. If we estimate that the TS content is about 12% and VS content about 80%, we get a load of about 1kg Vs/day/cubic meter, which is good for a non-stirred plant.*

The HRT depends of the size of granularity/particle size of the input. It also depends on temperature but this parameter is harder to take into account in calculations as the difference of productivity between 20°C and 35°C is still to test on this plant.

Calculation for hydraulic retention time (HRT) : HRT = V/Q
With V: volume of digester (L) and Q: loading rate (solid + liquid) (L/day)

3. Monitoring – measurements

Installation of the tarp was the first step.

Figure 6: installation of the tarp

Inoculation: Digester have been inoculated and started with around 1.5m^3 of cow dung. Straws, rocks and impurities were removed during mixing with water. 3000L of water were added

The starting process was longer than expected as the 2 first tanks tried turned out to be defective (the all matter had to be removed with seal and put in other tanks) and successive water cut occurs during 1 week...

Figure 8: arrival of cow dung from the neighborhoods

Figure 9: digester 1 day after inoculation

Once the 2 digester started:

Inputs (kitchen waste) were collected in a hotel and a scholar canteen every week and brought to the site with a tractor. Impurities as plastics, wood.were removed before charging in the tank.

Figure 10: loading of the sorting tank

Figure 7: Kitchen waste collected in blue tanks and brought with a tractor

During 2 months, digesters were regularly feed with 9 to 18kg of waste (weighed). In digester 1, all size of inputs was added. In digester 2, only inputs of less than 7cm were added. 10 kg of inputs were mixed with 20l of water.

Figure 12:loading of kitchen waste of all size

Figure 11: Digester full after 10 days without using biogas

As inlet pipes were too small, an intense mixing was done with a wood pole.

For the biogas: water was removed in a condensation box (small plastic box). It was desulfurized with pellets containing ferrous oxide. Both were in the “kit” of Asense company (Asense sarl, s. d.). The gas passed through the gas meter just before reaching the burner. Cooking times were recorded on the kitchen stove and on the burners of the drying unit during a drying of fruits.

Temperature inside the digester was measured with a thermometer fixed to a flexible hose. With this system it was possible to pass the thermometer between the wall and the tarp to measure the temperature inside.
pH was regularly measured with pH paper.

The experiment lasts 3 months. The last month, no inputs were loaded. The experiment was conducted this way for 2 reasons:

- It was not possible to load every day the same amount of waste has we were not always on site and there was some incomprehension with peoples in charge during these absences
- The amount of available feedstock was not sufficient to have a real continuous process with an HRT of 45 days to 60 days.

As a consequence, the goal was to obtain the all gas possible to have with the inputs loaded to check if feedstock 1 (all size of inputs) would produce the same amount of gas than feedstock 2 (small size of inputs) but on a longer period. The experiment stops when almost no gas was produced, meaning that the all methane potential had been used.

4. Results – discussion

Tableau 2:comparison of 2 feedstock on gas production and consumption on a kitchen stove

	Digester 1: all size of inputs	Digester 2: small inputs (≤7 cm)
Total inputs	1.5m3 cow dung + 333kg organic waste	1.5m3 cow dung + 348kg organic waste
gas produced by cow dung after inoculation[m3]	≈ 3	≈ 3
Time between inoculation and inflammable biogas [days]	18	10
Total volume of gas produced in 3 months [m3]	17	25
Total organic waste loaded in 2 months [kg]	334	348
Total gas produce from organic waste [m3]	14	22
kilogram of organic waste necessary to produce 1m3 of gas	**23**	**16**
Average consumption of the kitchen stove [L/h]	457	428

Digester 2 produced 8 cubic meters more of biogas than digester 1 for only 15kg of supplementary waste in digester 2. The quantity of feedstock necessary to produced 1m^3 of gas was smaller for digester 2. **This confirms that smaller particles size allows better yields** (Eawag 2014)**.** Maybe the digester 1 would have produced the same amount of gas if we would have wait one month more (to achieve 60 day of HRT for the last inputs loaded) but it is not sure as it has been shown that small particles size facilitates tremendously the activity of microorganisms during the AD process (Monge, Certucha Barragn, et Almendariz Tapi 2013) and when the experiment stopped, almost no gas was produced.

pH was stable, between 6.76 and 7.13 on both digester for the duration of the experiment.

From March to June, temperature inside the tank decrease from 21°C to 19°C, and this is very low for an AD process. That can explain the low yields obtained. However, the digestion was still taking place as biogas continues to be produced. The process was just much slower than it could be during the hot season. One of the experiments that really have to be done on this plant is to do the same but during the hot season in order to compare gas production rates.

Laboratory measurements:

All the measures should have been done regularly to give representative results. However, the time was limited as it took 2 month to have all the necessary material for experiments and then, the other studies had to be done too so experiments have been done punctually and results for gas quality, %TS, A/TIC and C:N ratio are not representatives.

%TS: in average, feedstock loaded had about 88% of moisture content, meaning that in contains about **12% of TS.**

Gas quality:

Digester 2 presents also better gas quality as less volume of gas is necessary to boil 1 liter of water. It took 5 min and 56 s to boil 1L of water with the gas from digester 2 and 6 min 42 in the same conditions with the gas from plant 1.

Plant	% of CH_4
Digester 1	72.5
Digester 2	68.5

Test syringe: This measurement is not accurate and the NaOH was probably not pure. That is the reason why the biogas seems to be a “high quality biogas” containing high percentage of methane.

Digestate characterisation:

The digestate can be considered as wet as it contained less than 10% of TS

	Shimadzu TOC-V				
Sample	TOC mg/l	TIC mg/l	TN mg/l	C total mg/l	C:N
DIG 1	394.1	236.4	112.7	630.5	5.6
DIG 2	252.5	219.4	80.3	471.9	5.9

The only times it was possible to do measurements for C:N ratio of effluent, the ratio was between 5 and 6 for both digesters.

Ammonia and organic nitrogen, determined by Kjedahl titration, shows a high proportion of ammonia and organic nitrogen compare to total nitrogen, indicating that little nitrogen is mineral and directly bio available(ADA 2016). However, N amounts are sufficient to affirm that digestate can be use as fertilizer, organic N will be transformed by soils microorganisms. But it has to be use with precaution (as explain in section IV, post treatment of feedstock). Ideally, C:N ratio should be around 15(Eawag 2014). It would have better fertilizing quantity. It is possible to control the C:N of the feedstock, which have been shown to influence biogas methane yield during digestion and also C:N ratio of sorting digestate. To increase C:N of feed stock, C-rich elements (House 2006)as grass, organic wastes (but it is what we already had), leaves... No manure should be added as manure is N-rich and decrease C:N ratios.

kjedahl titration mg/L	Kapp titration		
TKN mg/l	TIC mg/l	VFA mg/l	A/TIC
88	185	47.4	0.26
68	189	57.4	0.30

A/TIC was normally under 1. The experiment has been done 3 times on a 1month and a half period. Results were for both digesters, always comprised between 0.2 and 0.5, indicating a stable process(Buchauer 1998).

5. Limits of this experiment

This experiment has limited « scientific » value for many reasons:

- The main purpose was to set up an experimental protocol. As a consequence, modifications on the protocol were done during the experiment so it is not really reproducible
- The quantities of inputs available were not sufficient to have the digester really working in continuous, it was more semi-batch conditions
- Incomprehension with technicians helping for the experiments lead to some errors in the protocol
- The quality of chemical products used seems to be really questionable, which hinder tremendously good measurements.
- The material available was limited, thus some experiments were not feasible (the Carbon Oxygen Demand COD for example, which is an important parameter to give for use of wastewaters or in our case, digestate or the P and K total in order to evaluate the quality of digestate as fertilizer).
- Quantities of solid inputs are very approximate as it was not possible to determine either TS or VS.
- It was difficult to follow a rigorous protocol in the context of Madagascar as unforeseen events are always happening (water and power cuts, breakdown of the tractor in charge of the supply in waste...)

6. Conclusion

The set up of an experimental protocol has been successfully done. Students or other interested people can know come to the AD facility and follow a protocol for measurements on biogas productivity in function of feedstock, water ratio and temperature... Measurements in the laboratory are still to improve but some can already be done.

It has been shown that a feedstock of less than 7cm produce 1.5 time more biogas than a feedstock with all size of particles. The C:N ratio of about 5 was found, confirming the interest as fertilizer for the elevated nitrogen content. This ratio should be increase to 15 by adding more C-rich elements in the feedstock.
The consumption of the kitchen stove and the burner in the dryer were established, being around 445L/hour and 1100L/hour respectively. The consumption also vary depending of the AD plant connected, showing a difference in gas quality.

Results of this experiment are to take carefully, due to all the limitations mentioned above. However, it can be include in the few "scientific" experiments conducted on AD with kitchen waste in Madagascar. It is a step forward for research on AD in the country. If this facility can serve to Malagasy student to train on AD, even if the accuracy of measurements is not perfect, it is already a progress.

III. Assessment of the potential of biogas as fuel for a drying unit and proposition of a supply strategy

Annexe: Note of recommendation for current use of the AD plant of the drying unit (in French)

1. Situation

The PATMAD and CEAS own a drying unit for vegetables and fruits. Products from the region are dried by a cooperative of farmers and sold by the NGOs, mostly for export. For the farmers it is a secondary activity that assures a small amount of money when harvest is bad.

The drying is done either with solar dryer (for local consumption) or with gas (mostly to export). Gas is expensive in Madagascar, for the drying, it represents 25 to 30% of the budget. That is why 4 AD plants were built in 2012. However, due to problems to find inputs, the plant was not used for 2 years. The only input used previously was cow dung. As all the farmers use it for the field, no one agrees to sell regularly the dung. That is the reason why they stopped using the biogas facility. One of the objectives of the project was to propose solutions for this supply issue. An accommodation centre is also part of the propriety.

It was decided to focus on kitchen wastes as input to solve the problem of supply.

2. Technical parameters

The AD plant is the one described in the section II.

a) Needs for the drying unit

A drying session last from 18h to 32h, depending of the fruits. Around 500kg of fruits are dried per session in 4 dryers.

Tableau 3: Values for calculations

10 - 20 kg organic kitchen waste ≈ **1m^3** biogas
1m^3 biogas ≈ **2.5 h** of cooking on kitchen stove
1m^3 biogas ≈ 6 kWh ≈ **2kWh** in electricity
Density of kitchen waste from the drying unit ≈ 700 kg/ m^3
Density of kitchen waste from hotels ≈ 600 - 700 kg/ m^3

Values used for calculations are based on experiments (see section I) and on literature(Eawag 2014).

Tableau 4: facts concerning consumption and costs for cooking fuel in the drying unit and the kitchen of the drying unit

Data for the drying process with gas	1 drying : 18-36h
Price gas cylinder 12kg [Ar]	70 500
Gas consumption for drying with gas cylinder [kg gas/h/dryer]	**0.4 to 0.6**
24h of drying	≈ 1gas cylinder of 12kg/dryer
Price of 1 cooking hour with gas cylinder [Ar/h]	**2938**
Gas consumption with biogas [L gas/h/dryer]	**1100**
Price of 1 cooking hour with biogas [Ar/h]	depends of the source of waste
Data for the kitchen of the accommodation centre	
Cost for cooking fuel charcoal per month [Ar]	12 000 – 20 000
Daily time of cooking [h/day]	3
Gas consumption with biogas on the kitchen stove [L gas/h]	**440**

b) Energetic potential of the AD plant

Tableau 5: comparison of HRT, daily loading rate, gas produced, potential cooking time and advantages/shortcomings balance with and without mechanical pre treatment of feedstock

	Without mechanical pre-treatment	**With mechanical pre-treatment, particle size ≤ 5cm**
Advised HRT (House 2006) (days)	60	30
Maximal total inputs per day(kg)	75	150
Of which water (L)	50	100
Of which solid input (kg)	25	50
Daily gas production(m3)	1 - 2	2 - 3
Daily digestate released (L)	20	40
Corresponding cooking time per day on the kitchen stove (hour)	2 - 4	4 - 6
Corresponding cooking time per day in a dryer (4 little burners) (hour)	1 - 2	2 – 3
advantages	Easy and fast	Higher rate of gas production ↔better yield
	No investment necessary	Low risks of blocking the inlet pipe
		Inputs entirely digest, no remaining pieces in digestate
shortcomings	Low rate of gas production ↔lower yield	Investment necessary
	high risks of blocking the inlet pipe, regular control and mixing in the inlet pipe necessary	Grinding is an additional task
	Digestat may contain non digest pieces	

Theoretically, each digester (there are 4) could process 50kg of waste per day if the feedstock is mechanically pre-treated. 25kg if it is not. That would produce between 1 to 3 m^3 of biogas per day and per digester.

c) Potential sources of organic waste

Tableau 6: summary of currently accessible organic waste

Potential sources of Organic waste	quantity [kg/week]
Kavitaha Hotel	150
Catholic school (canteen)	50
Kitchen of the centre	25
garden	5
Waste of fruits from drying	?
Total minimum per week	230
Total minimum per month	**920**

-Waste from the Kavitaha Hotel and the Catholic school were used during this study for experimentation. That is the reason why it was possible to quantify them and confirm that there are able to furnish relatively well-sorted organic waste.

- An unknown parameter is the quantity of waste generated during the preparation of the fruits for drying process as this study was done in a non-producing period. It was possible to estimate the percentage of waste on total weight per fruits just for pineapple (40%) and physalis (12.5%) as we did an experimentation of drying with biogas for theses fruits.

The NGO will have to quantify later the percentage of waste on total weight for each fruits in order to organize drying sessions in function of needs for biogas and quantity of waste available (to produce biogas). As the plan for drying is done monthly, it will be possible to do this kind of anticipations.

d) Potential transport available to collect waste

Private tractor: expensive (20 000Ar/drive) and not environmentally friendly (transport waste on 6km with a
tractor to produce biogas is not interesting if the idea is originally to produce renewable energy).

Zebu chariot: expensive (16 000 Ar/drive) but ecological

Closed tanks on the roof of a **"taxi brousse"** : around 4000Ar/drive but 2 drive necessary as it is not possible
to transport 150kg of waste in one closed tank. Thus it would cost 8000Ar per drive.

The transport is the main issue for the supply strategy of this AD facility.

e) Stakeholders

Stakeholders involved for the AD chain are not so many.

In the drying unit:

2 employees of PATMAD could potentially be responsible of the plants, the cook or the laboratory technician. They should follow a small formation for the maintenance of AD facility and to manage it. The responsible would be in charge for the all AD process, from collecting organic waste, transport, contacting potential waste producer, doing the drying plan in function of the needs of biogas, delivery of digestate, maintenance...

The **2 NGOs involved in the drying unit**: they will have to discuss and chose a strategy for the future of this AD facility.

Provider of waste: institutions in the village are important waste generator. It is necessary to talk with them and explain them the request for organic waste in order to known if they would agree to sort out their waste. This process has been done with the Catholic school and one Hotel and they directly agree to collaborate.

Local farmers: the responsible should discuss with them in order to know if some of them would be interested to punctually exchange some seal of cow dung or pig manure with tanks of digestate.

Members of the cooperative: maybe they could organize themselves to find sources of waste. However, as their salary do not depend of the cost of the process or sales of the products, (they are hourly paid with the minimal salary), they will likely do not care of saving money by buying less gas cylinders.

Transport: an agreement should be concluded with somebody to do the transportation of waste every week.

f) Parameters to consider

Temperature:

The drying unit is working from October to Mars, which correspond to the « hot season » in Madagascar. In Ampéfy annual temperatures are: (Climate data 2016)

- Octobre - Mars : 14°C à 35°C
- Avril – Septembre : 10°C à 26°C

The AD plant could reach optimal temperature during the drying period, leading to efficient digestion(Donoso-Bravo et al. 2009), which is a favourable argument to use the AD plant to dry fruits. During the cold season, AD plant could be use minimally (as it has been shown in the previous section that the process keep going but idle), just to maintain the bacterial flora. Annual maintenance, draining and cleaning of the tank could be done at this period.

Use of digestate:

The digestate could be use for the numerous plantations of the drying unit and gift to the farmers from the neighbourhood, who are members of the cooperative working in the drying unit.

Storage of gas:

Needs in gas for the drying unit are not really adapted to this type of AD technology. Indeed, small AD plant of this type are able to furnish daily regular quantities of gas but are not built to furnish 24h of cooking time each 2 weeks, as the drying process require.

This is the reason why a storage solution could be considered. Storage of biogas is difficult. What exist on the market are: low pressure bags for storage, medium pressure storage system or high pressure system. In Madagascar, no systems of storage are on the market, which means that the device should be imported.

Low pressure bag on the market are expensive (around 50euro/cubic meter) (Puxin company 2016). Maybe that it could be built in the country but bags are fragile, UV and temperature sensitive and very voluminous. (See section I for precisions).
Medium pressure system (around 10 bars) are interesting as only 3 to 4% of the energy of the biogas is necessary to compress it and it can be achieved with a compressor.
High pressure systems are not suitable in our case.

Storage could be considered if a sufficient source of waste is found. However, investments costs are elevated so the solution may not provided a sufficient financial interest.

The unique simple, cheap and small storage that could be done is to use one of the 4 digester as a storage tank. The digester would be filled only with water and gas from other digester would be transferred into it with the compressor available. 4m^3 of biogas could be stored with this solution. It is a good option if there is not enough inputs to feed the 4 plants.

3. Propositions

As the AD plant is already built, it would be a shame not to use it. The following analysis proposes 2 scenari. One « minimal use » scenario that could be sufficient just to provide the accommodation’s kitchen of the centre in gas. The other, a “full operational “scenario, to feed dryers in gas completed with some gas cylinders during the drying process.

a) « minimal use » scenario

In this scenario, only 1 plant would be working. The digester would be loaded only with waste from the kitchen and the garden of the drying unit. Gas produced would just limit the use of charcoal to cook.

Tableau 7: balance sheet of costs for cooking fuel in the kitchen and potentials savings using 1 AD plant

	charcoal	biogas	
Price of the bag (30kg) [Ar]	12000		
Biogas possible to produce per month [m3]		8 -12	Calculation for about 35kg of loaded waste / week
Cooking time per month [hours]	90		
Cooking time possible to furnish per month [m3]		16 - 24	
Cost per month	12000	0	
Cost per year [Ar]	144000	10000	Annual costs for the AD plant include one inoculation per year with $1m^3$ of cow dung
Price for cooking [Ar/h]	133	49	
Minimum savings thanks to bio gas [Ar]	17200		

With only 35kg of waste per week, the centre accommodation's kitchen could not be independent from charcoal. However **60kg of charcoal**, **which represent around 600kg of wood** (Ravoavison et Hofs 2008) **would be spared each year**. Even if the interest is limited on the financial point of view, it is environmentally very interesting.
Moreover, if more waste is produced or another source founded, more biogas will be produced.
As the place could potentially also serve as demonstration/experiment place for biogas, this option could be combined with this eventuality.

This scenario is not for optimal utilisation but as the plants are already built, it proposes a transitory plan to profit of the facility.

b) « Full operational » scenario

If the 4 plants were operational and, up to 200kg of waste mechanically pre-treated could be processed every day, generating 6 to $16m^3$ of biogas. This hypothesis is however not realistic for 2 reasons:

- If so much gas is produced, storage will be a problem and storage system will have to be considered, requiring supplementary investment
- Currently, no so important accessible source of waste has been identified

Therefore, the quantity of inputs is the limiting factor of the "maximal use" scenario.

The scenario is based on a weekly collect at the canteen of the catholic school and at the biggest hotel of the village. Two transports are considered: the tractor or the “taxi-brousse”. 3 digesters could be working and one used for the storage (as explain in the sub section f. “parameters to consider”).

Tableau 8: balance sheet of potential savings of gas and money by using AD facility or not for the drying process

	Gas cylinder	Biogas, organic waste collected weekly with a tractor	Biogas, organic waste collected 2 times/week with a « taxi brousse »
Price per month [Ar]	Depends of the use	80000	32000
Maximum produced biogas per month [hour of drying on one dryer]		38	38
Price [Ar/h]	2938	2087	835
Minimal economy of gas cylin der per month [kg]		19	19
Minimal savings of money per month [Ar]		32604	80604

These calculations are based on « pessimistic values », which means that during the hot season; productivity could increase, leading to an increase of savings. If wastes from the drying activity are added as inputs, more gas could be generated.
The scenario shows savings of about 19kg of gas from cylinder and about 80 000Ar per month (if the taxi brousse solution is chosen).

To have the biogas even more interesting, it would be necessary:

- To find a cheaper transport

- To increase the quantity of collected waste (with the drying of fruits, ask to restaurants or other hotels of the centre, to farmers in exchange of digestate…)

This scenario should also include the use of the biogas on the kitchen stove of the accommodation centre when not used for the drying (outside the drying periods). If this scenario is chosen, designation of one responsible of the AD plant will be necessary. He will be in charge of the supply strategy, the daily load and forecasts so that the drying is partially made with biogas. He will have to learn to master the plant.
Some modifications of the facility should also be considered to have a perfectly operational plant (the necessary modifications/renovations have been listed in a document apart intended to the NGOs).

Conclusion - Recommandations

The drying unit cannot pretend to a total autonomy in gas with the existing AD facility. However, the consumption of gas cylinder could be reduced. As plants are already built, it would be a pity not to use them. The centre accommodation’s kitchen could work with biogas, which would be the minimum. For bigger ambition, the facility should be revised and completed with a grinder/shredder in order to be fully operational. With the present researches for a supply strategy, biogas is economically not very interesting, but still represents small savings of money (1 cylinder ok 12kg per month) and clear environment benefits. The site could also become a “research – training center” for AD as one of the purpose of the NGOs is to promote sustainable energies. Many options and projects can be achieved with this AD facility; it is now a question of choice. Whatever the option chosen, a responsible in charge of the plants should be clearly designated.

IV. Feasibility study for the valorization of organic waste through anaerobic digestion in a rural municipality of Madagascar

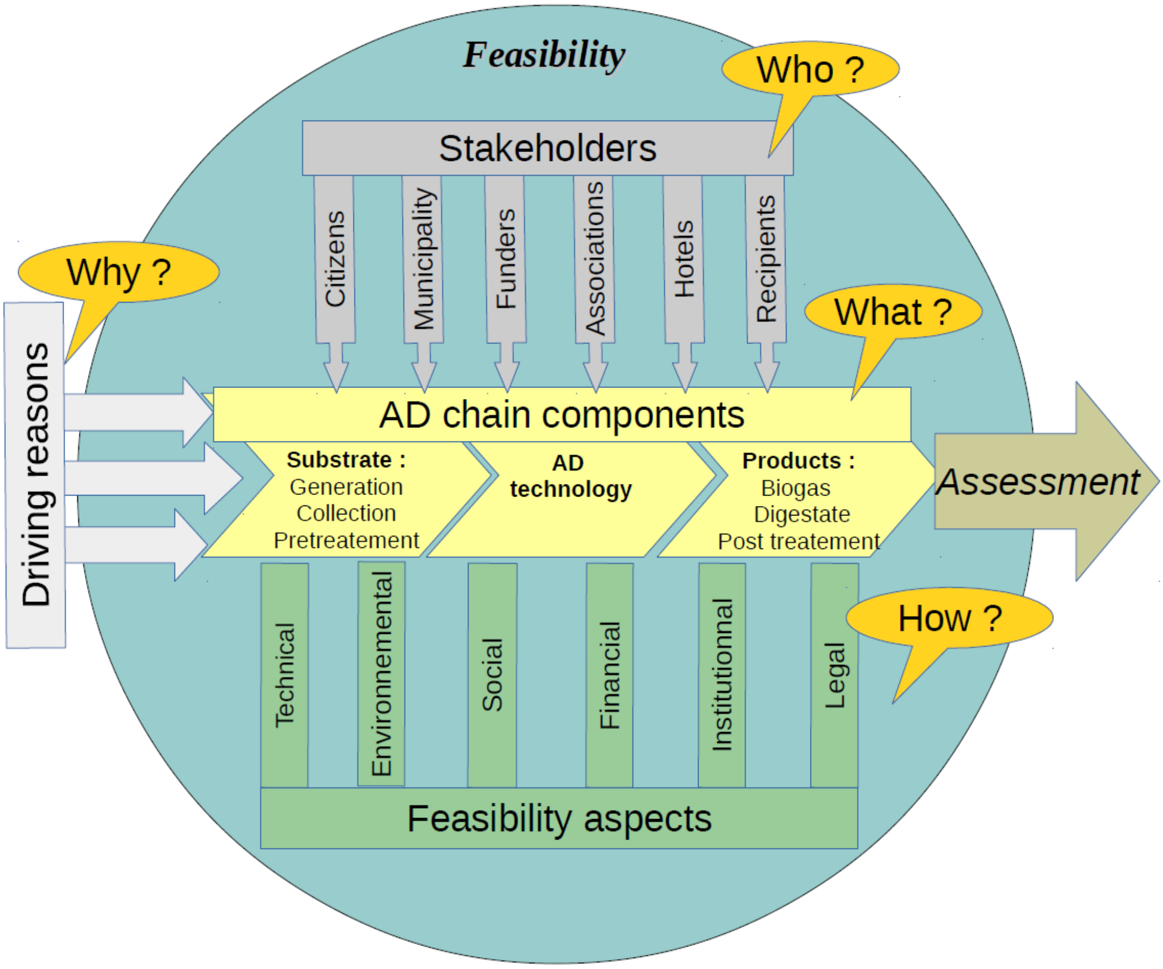

Figure 13: general framework followed for the feasibility study (inspired by Lohri, 2012)

This feasibility study was carried out following this scheme. The purpose is to consider all the aspects mentioned on the scheme. It can be simplified with the 4 basics questions: What? Why? How? Who? This section mostly answer to the How, considering the 6 feasibility aspects and the Who, identifying all the stakeholders in the village. Driving reasons for AD and the description of the technology have already been explained in the introduction.

Figure 14: map of Madagascar, in red the region Itasy, were is located Ampéfy.
Source:https://fr.wikipedia.org/wiki/Itasy

1. Geographical and socio economical situation of Ampefy

Ampéfy is a rural municipality in the centre of Madagascar, along the lake Itasy. The county seat counts around 3410 inhabitants (Mairie d'Ampéfy 2011). The municipality is constituted of 13 Fokontany (local denomination for sort of district authorities); in total it represents 18000 inhabitants.
The village is touristic. Because of the lake and the beauty of the region, it is one of the favourite places for people from the capital to spend the weekend. For this reason, there are about 12 hotels/restaurants in the area. The frequentation of the region will increase in few years, when a main road will pass by the village.
There are no economic activities except food crop and fishing. As the region is quite fertile, most of the population has agriculture as a source of live hood.

2. Legislation

In Madagascar, there is no regulation concerning the sector of renewable energies, it does not seem to be a priority for the government.

For the SWM, 3 texts, the law 2014-018 (Assemblée Nationale de la république de Madagascar 2014), 2014-020 (art 232 – « droit de demande de redevance pour gestion déchets ménagers ») about decentralisation and the « water code » (sous section 2)(Assemblée Nationale de la république de Madagascar 1999) stipulate that the SWM is the duty of municipalities. However, modalities are not stated, which let the regulation very soft. Moreover, there is no control of the state on municipalities on this topic. SWM is not a priority. This is the reason why some municipalities do not have any SWM politics and budget, other do. It is the case of Ampéfy.

3. Current situation of solid waste management in the village

Annual budget for SWM represents 4 to 5% of the municipal budget. Currently there is:

- 3 sweepers for the market and Main Street working every morning

- 2 municipal bins, one in the market, one near the hospital, emptied by the 3 sweeper and 1 tractor once a week. They bring the waste to the landfill.
- 1 « official » dumpsite /landfill on a private property in the village(authorized to plug an erosion hole)

The landfill was supposed to be full 3 years ago (Houmard 2012). It is still used. It is hard to predict when it will be completely full but it should be in a few months as the hole of erosion is not visible anymore.
Water continues to flow nearby the dumpsite. In the border of the dumpsite, wastes are now carry out by water during the rainy season and directly released in the lake 500 meter downstream.

Figure 15: the "official" dumpsite of Ampéfy, situated at 500m of the centre

Figure 16: hole of erosion filled with waste. As the dumpsite is now full, they discharge waste in this hole, which is the only space available. Below, a small river flows,carrying some waste directly to the lake.

A new dumping site has been identified. However, it is 6km far from the centre so the cost of fuel will increase. That is why the current dumping site is still used.

4. Social aspects

The social aspects mentioned in this work are the results of a population and hotels survey carried out about individual waste management and interest for biogas

For detail on this study, see "etude socio economique sur la gestion des déchets et le potentiel pour la valorisation des déchets organique par méthanisation »(Ravalison et Balmer ,2016)

In collaboration with a student in sociology from the University of Antananarivo, a socio-economical survey was done. The survey was about individual waste management in the household, fuel used for cooking, opinion on the MSWM and finally knowledge/interest on biogas.

This survey was necessary:

- to know current practices in SWM
- to have an idea of quantities of waste generated in each household and hotel
- to give an overview of the acceptance or no of a potential AD plant in the village
- to identified cooking fuel and quantify the need of hotels and households

a) Method

30 persons and 10 managers of hotel/restaurants were interviewed in the village. They were randomly chosen. Multiples choice questionnaire was used.

b) Results

Sorting: In Ampéfy, 50 % of the population of investigation makes no form of sorting. Other half separates organic waste from the rest to feed animals or to make some compost.
Most of hotelkeepers are sorting waste in order to give plastic bottle to the informal sector and to burn all the non-biodegradable waste.

Waste treatment: The Lava-Pako is the most wide-spread practice "to handle" household waste. The municipal bin is used by approximately 25 % of the questioned households. Some hotels are using it too but most of them have their own system.

Note : the Lava-pako is the traditional way of treating waste. It is simply a hole were the household burry all the waste. People who use to employ the resulting compost water the hole regularly and mix it. Non biodegradable elements are either separated afterwards or simply spread on the fields with the compost.

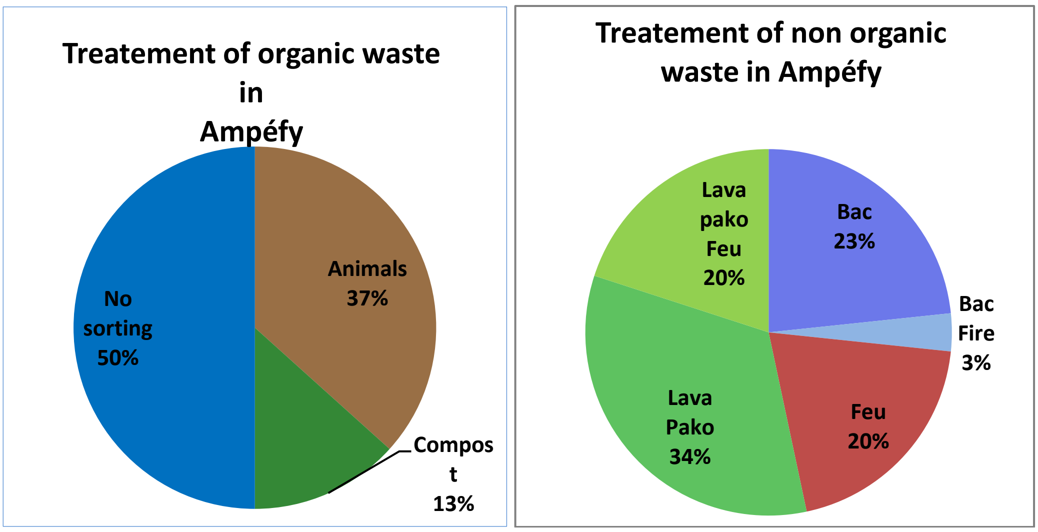

Figure 17: Results of the survey concerning treatment of organic and non organic waste in Ampéfy

Collection: The idea of a possible collection was mentioned. The majority of the population shows interest and would, theoretically, agree to pay a small fee for this service. However, they would not agree to walk more than 100 meter to reach the collection point. Frequency of collection should be on a daily base or at least twice a week. Hotels are also interested and would agree to pay an elevated fee (compare to household) for collection.
The majority of the questioned population claim to be ready to sort out there waste for a sorted collect with organic waste beside.

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Biogas: according to the majority, SWM is the responsibility of citizens and municipality. However it seems that population is not satisfied by the MSWM.

Concerning the biogas, approximately 66 % of respondents do not know the system but most of the people show interest. It is possible to correlate the interest and the theoretical acceptance of a biogas system with the level of education. The most educated are the most sensitive to the subject. **Hotelkeepers seem very interested to install AD plants as they have a big gas bill each month and are already sensitized on environmental questions.**

c) Discussion- conclusion

These results are of course to consider with caution. First because surveys are supposed to give tendencies but are not exacts. Secondly because regarding waste, people do not always act as they pretend to.
The *Lava-pako* is a good solution at the moment as the municipality is not able to treat all the MSW. To improve the MSWM, additional bins could be provided or a collection could be organised on a voluntary base with small subscriptions.
It seems that a project of valorisation of organic waste by methanisation could be well accepted by the population as citizens wish a better MSWM. Moreover, it seems that sufficient amount of organic waste are generated in the village to consider a valorisation solution.

5. Technical aspects

a) Identification of sources of waste

Most of wastes in the village are coming from household as the market is small and there are no industries. Hotels are producing only a small portion of MSW. For this reason, in order to collect organic waste and produce biogas, 2 ideas have been identified:

- Recycling and manual sorting of the waste from municipal bin
- organization of a door to door sorted collection

b) Quantification of wastes and fluxes

method

Waste from:

3 households of different living standards, 1 small restaurant of the market, 2 Hotels (the biggest of the village and a “medium one”), have been characterized on a one week period.

Figure 18: up on the left: sample of the organic fraction of MSW. Others pictures: waste of the 2 municipal bins

Figure 19: common type of organic waste generated on the market place

Samples of market waste and municipal bin waste have also been characterized. The sampling was done with the method of the “quarter”(Ouedraougo 2008) from the ADEME (the all mass of waste was mixed, divided and different part of the mixed mass were taken). Characterisation was simply a separation of each type of waste and the determination of their mass proportion.

Results were then compared with those from the survey, the observation of the weekly transport to landfill and municipal bins and some data from literature about waste in Madagascar. With all these information, we were able to identify and quantify the waste fluxes in the village.

Results

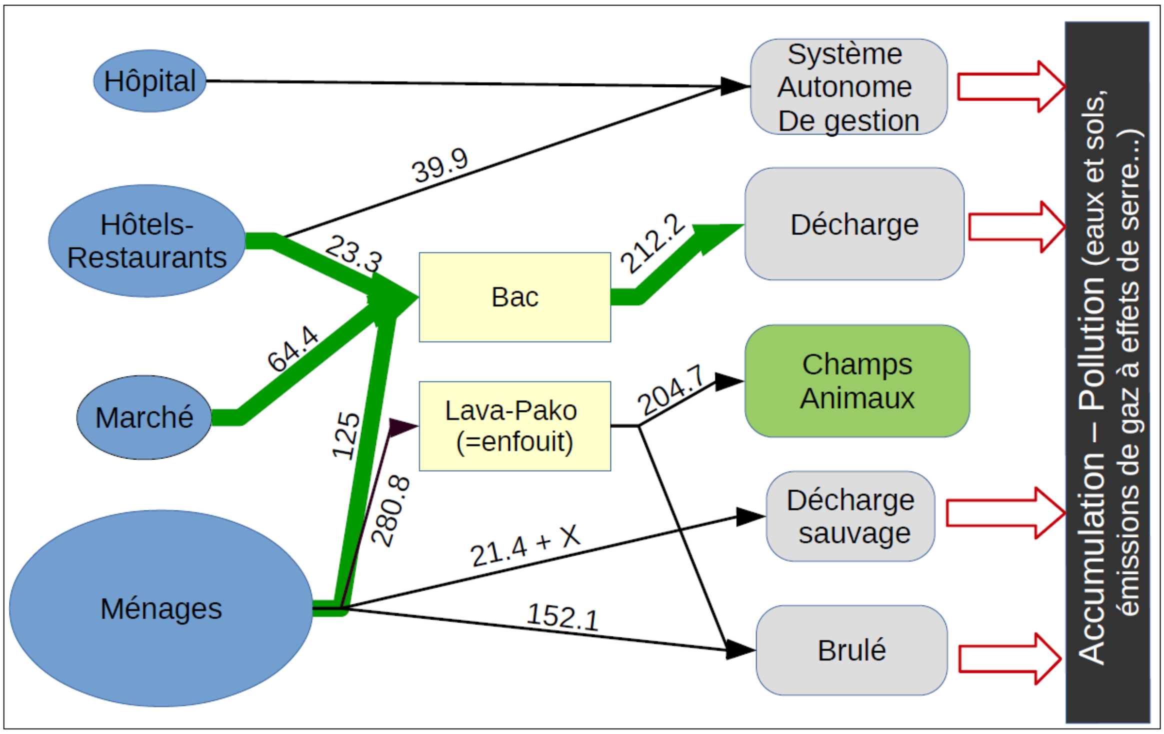

Figure 20: Fluxes of waste in tons/year in Ampéfy (in green: flux containing organic waste non recycled yet)

For details on data and calculations, see appendix 1.

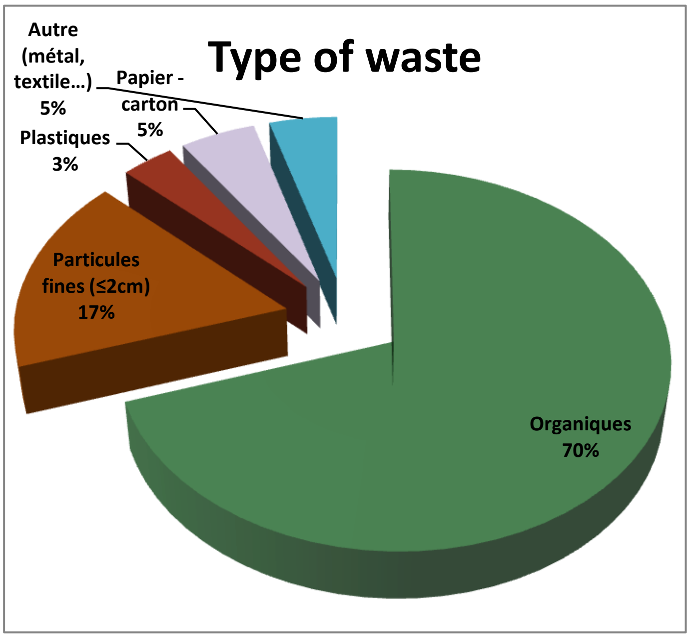

Figure 21: proportions of each fraction of waste in the municipal bin

One inhabitant from Ampéfy produces around 0.5kg of waste every day. Organic waste represents 70% of the total MSW. Wastes from hotels represent only 10% of all MSW. The market generates around 1.25 tons of waste weekly. Municipal bins collect 30% of total waste. Quantification of waste throw in unauthorized dump-sites as canalisations, fields and lake, is difficult. It has been estimated that it is a minimum of 21ton annual.

The *Lava Pako* practice treats 40% of MSW. Most of burnt wastes are the non-biodegradable ones because peoples do not know what to do with it.

Discussion

The MSW are mainly composed of organic waste because:

- All the glass bottles are returnable
- The plastic fraction is not so important as plastic bags are theoretically prohibited since 2015 (thus, this fraction should not increase).
- Low incomes countries have big proportion of organic waste because the use of many packaging is correlated to wealth (Hoornweg et Bhada-Tata 2012; Sandec 2016).

The average of 0.5kg/capita/day is high for a rural municipality in Madagascar. Maybe it is slightly overestimated. However, it should not be below 0.3kg/capita/day. The *Lava Pako* is a good solution for the valorisation of organic waste. It brings compost for the farmers and is a sort of « decentralized » valorisation that the municipality do not have to take over. It is a proof that the need for compost is high.

The fraction of organic waste that is not recycled is less than the half. However, it represents around 500kg of waste every week. Currently, these wastes are buried in the dumpsite, generating methane emissions if they decompose in an anaerobic process. Moreover, it fills the dumpsite while it is already full, provokes unpleasant odours, brings rodents and insects on site, in the centre of the village, and provokes generation of polluting lixiviates.

Conclusion

The quantification indicates that enough organic waste is generated in the village to consider the implementation of an AD plant to recycle the organic fraction of MSW.

c) Quantification of energetic potential for anaerobic digestion

As explain previously, ***2*** **options are possible to recycle a fraction of the organic waste. Whether the sorting of municipal bins or the organization of a collection.**

- Sorting of the bins :

This option present one advantage: As bins are built and 3 sweepers already paid, this option would require very few investments. Only the construction of 1 or 2 additional bins and the augmentation of salary for the sweepers would be necessary as they would work the all day long and not only in the morning.

2 big cities in Madagascar(Calmettes 2013; Le relais Fianarantsoa 2013) opted for this option because it creates jobs and do not require sensitisation of all population as necessary for a primary collection. However, the quality of inputs for AD will be bad.

- Collection :

The collect could be partially paid by subscriptions. This kind of systems has already been tested in many developing countries(Manus Coffey & Adrian Coad 2016; Sandec 2016) and presents advantages. For example, the price can vary in function of the sorting. It could cost 1000 Ar/month/household for sorted wastes and 2000Ar for household who do not want to sort wastes. It is also possible to do the primary collect only for people who agree to separate waste.

Hotels would also participate and their financial contribution would be much higher, which could help to have a self supported system.

A door to door collect seem more adequate in this context as it solves many problems:

- no contamination of the organic fraction
- no deposition of waste: no problems with dogs rummaging the bins
- control of the sorting by collectors

Disadvantages:

- not everybody can afford a subscription for waste collection
- Collectors need to be hire to complete the “team” of the sweeper/collector
- Collection vehicles necessary (basic chariot for example)

Tableau 9: quantification of OFMSW not recycled yet, whether collected or recovered in the municipal bins, energetic potential that it represents in volume of biogas, cooking time and electricity and the required digester size

	OFMSW not recycled yet [tons/year]	Hypothetical percentage of collection [% of total waste]	Organic waste collected for valorisation [tons/year]	Daily solid input [kg]	Biogas produced [m3/day]	Cooking time [hour/ day]	electricity [kWh]/ day	digester size (HRT 45j) [m3]
Scenario collection								
Households	407	25	102	279	16	41	33	38
Hotels / Restaurants	25	80	20	56	3	8	7	8
Market + public bins	100	100	100	274	16	40	32	37
Total	533	31	222	609	36	90	72	82
Scenario bins								
Municipal bins	164	23	164	448	26	66	53	61

Rate of collection is difficult to estimate not knowing how many people would really want to participate. In this scenario, 25 % of the households are taking part.

The waste of the municipal bins would be sufficient to produce 53 kWh per day or supply 66 hours of cooking. With a collection (but figures are hypothetical), it would be possible to supply 72 kWh per day.

Considering only the waste of the bins, a $61m^3$ digester would be needed if inputs are not mechanically pre-treated.

The limiting factor for valorisation of organic waste by « low tech » AD is the capacity of the digester and not the quantity of inputs (see below the subsection "choice of the digester" for further explanations). That is why the solution of many small AD plants with distribution of inputs has to be considered.

A scenario including faecal sludge as input could also have been done. This option is interesting to treat faecal sludge but not to produce big amount of biogas as the BMP of faecal sludge is much lower than the one of OMSW(représentant AFD 2016; Estoppey 2010). This option has not been considered because acceptance of the system seems much more difficult and use of digestate from faecal sludge require long post treatment(Segretain 2016; Eawag 2014) to avoid problem with pathogens as bacteria, helminths.... In a first phase it is easier not to use this kind of input but it is perfectly feasible to add this option after a time, when interest on valorisation of waste will have increased.

For the inputs, it is important to consider annual variation of quantity, quality…Using OFMSW, variations should be slight. Maybe some changes will appear with the rainy season or the cold season (less fruits and vegetables are growing at this period).

In Ampéfy, the AD plant could be in function during all the year as temperatures are never below 9°C. However, gas production rate will vary during the year as digestion is strongly influenced by temperature(Donoso-Bravo et al. 2009; House 2006). In the hot season (october – mars) the temperature inside the AD plants may reach 35°C and yield will be good. During the winter, temperature in the plant will probably be around 20 – 25°C and digestion will be much slower.

d) Choose of AD type and digester

In the context of Ampefy, the AD plant should be simple, cheap and robust. The facility should be built with local materials and competences. Generally, this kind of installation "low tech" does not exceed 30 – 40 m^3. Beyond this size, stirring and heating of the tank are required, which makes the system much more complicated.
Choices for the type of AD plant for Ampefy are deduced from these criteria.

Dry/wet way

Several modes of fermentation are possible for AD. For dry fermentation, the total quantity of solids exceeds 16 % (Eawag 2014; House 2006).In developing countries, the dry way would be the most logical because it is cheaper, needs in waters are reduced and the technology more simple. However, dry systems are often batch system(Burri et Martius 2011). As a consequence, the gas production is not continuous.

Moreover, the majority of the systems set up in developing countries (and it is also the case in Madagascar), are systems by wet way because they allow a continuous supply and thus a continuous production of gas. The quality of produced gas is also more stable.
The AD plant should be a continuous or semi batch plant with wet fermentation.

Digestion will of course be a **mesophilic digestion** has local temperatures allows it and mesophilic process is much simplest to implement than thermophilic process.

The type of digester will **be a floated dome of fixed dome** as some plants have already been installed in the country, local competences will be required. Moreover they are robust and build with local material.

Pre treatment of feedstock

Sorting: the ideal is source separation to obtain good quality of inputs Good inputs will lead to better digestion and produce digestate of high quality, free of contaminants. .(source management digestate).
Households and hotels would have 2 bins: one for organics, the other one for the rest. It avoids manual sorting and contamination of inputs by small pieces of plastic, sand and unwanted chemical compounds (heavy metals…). If the source separation is impossible, then people will have to sort out manually waste. It is a tedious and difficult work.

Grinding/shredding: mechanical pre treatment of input present two main advantages:
It reduces the risk of obstruction of the inlet pipe (Eawag 2014)(experimentations in section II).
It enhance the rate of digestion, so the biogas yield (on a certain period of time) (Schnurer et Jarvis 2010)as it increase the exchange surface and microorganisms can fix on the compound to digest it. It also reduces the time required for an input in the digester (Montgomery et Bochmann 2014)r. A simple mechanical or electrical grinder could be a good investment for the AD plant.

Pre fermentation: if there is no grinder/shredder, it is possible to make a pre-fermentation stage. It corresponds to a simple « multistage process ». Inputs are stored in a preliminary tank for about 3-4 days (Houllier 2016) so that the first 2 stages of the digestion (which does not require anaerobic conditions) are achieved in this tank. It reduces the HRT in the digester and thus the size of the digester for the same quantity of inputs. It also allows storing waste to check better the daily inputs. However the yield in methane can decrease slightly with this technique and odours will come from the preliminary tank(Eawag 2014).

Post treatment of feedstock and biogas

Biogas: The water will be removed by condensation in a water trap. Sulphur can be removed very simply with material containing ferrous oxide (possible to buy or to put a rusty iron sponge in a trap). If biogas is used to produce electricity, desulfurization is crucial to preserve the generator from corrosion. A real desulfurization device should be use(House 2006; Energypedia 2016).

Digestate: The liquid coming out of the digestion is rich in nutrients (Burri et Martius 2011; Sass 1998; Smit et Rigby 2011) as mineral nitrogen, phosphor and potassium. One advantage of digestion is the transformation of organic nitrogen into mineral nitrogen, the bio available form and the degradation of some unwanted compounds for soils (Al Seadi et Lukehurst 2012). However, it can also be "dangerous" as the digestate is liquid so the risks of washout and pollution of subterraneous water is present(Estoppey 2010). Moreover, an uncontrolled use of this fertilizer could burn the plants. These risks are present mostly for big plants, in our case, quantities are small and a local management could be possible without risking damages on environment.

Ideally, as digestate is a good fertilizer, it would be interesting to sell it and use this little money for maintenance for example. Selling digestate is however a major problem as composition of digestate is changing a lot depending on input and stability of digestion (Al Seadi et Lukehurst 2012; Smit et Rigby 2011). Moreover, some potentials chemical contaminants are not degraded during digestion.(reference digestate quality management).

As a consequence, the selling can only be limited to small and informed consumers. In Ampéfy, most of the farmers would be interested (result of the socio economic study). That would maybe not replace all fertilizers they use (because P and K values are often low in digestate but environmentally and financially it would be interesting.
To avoid problems of high concentrations and wash out of nitrogen, there is 2 solutions:

- Digestate can be systematically diluted with water (ratio 1:5 for example) before spreading on fields (House 2006)

- Digestate can be co-composted either with compost or with straw. (Bustamante et al. 2012; Segretain 2016) This solution is good because the result is a solid fertilizer, easier to handle, stable and mature. Moreover, it can enhance the rate of composting. If digestate is very liquid, solid and liquid can be separated to proceed to this treatment. (Sass 1998).

To avoid direct evaporation of ammonia during spreading, it should be done at the base of plants and can also be recovered with soil or straw.

Conditions for the AD facility

The AD plant should:

- Be located were waste are generated (in the centre of the village) to avoid transportation costs and pollution.
- Be however slightly removed to limit nuisances to the neighbourhood (odours mostly)
- Be easily accessible with a tractor
- Have an access to water (the process require a lot of water)

A big installation should include an area to sort out the waste, an area for the storage and the treatment of the outgoing digestat.
If there is several small AD plants distributed in the village, an area in centre will be necessary to sort the waste so that they can be later redistributed in every plant. Every AD plant will have to be accessible for a tractor.

e) Conclusion/proposal

Technically, it is feasible to value the OFMSW by AD. There is even more valued organic waste than what can treat a digester of 40m^3. The ideal would be the combination of AD and composting to produce, besides the gas, solid bio fertilizer for the farmers of the neighbourhoods.

6. Opportunities for utilisation of biogas in the village

Biogas has very different yields depending of its use. A use as cooking gas amounts to 100 % efficiency. The electricity production on the other hand offers only efficiency from 20 to 30 %, the rest of the energy being lost in heat. The biogas can also be used as fuel for refrigerators working with petrol or for gas lamps. That is why it is important to identify all the places in the village where it could be interesting in order to be able to choose which use of it will be more helpful.

If a lot of gas is produced, it is difficult to use everything as cooking gas because storage and/or transport are problematic. In this case electricity generation from biogas is favourable. It is also possible to use it to maintain the digester at 35°C to improve the digestion but in this context, this is not so suitable.

Health center CSB II

The Clinique hosts approximately 30 patients a day. Relatives of the patients bring him food or cook in a free access kitchen for him. Families bring their wood or charcoal for cooking. A meal represents approximately 400 Ar of charcoal. The wood is free.

Approximately 3 to 4 families cook every day a meal. 2 - 3 m^3 daily of biogas would be sufficient to cover the needs of all the users of the open kitchen. The use of the biogas could cost approximately 200 Ar / meals, it would be cheaper as the charcoal but not free. A person should however watch regularly to avoid problems (as nobody is used to cook with gas).

Figure 22: "free access" kitchen of the Hospital

This last point is important and if the idea of an AD plant for the CSBII is held, it will be necessary to find a solution to this question.

The centre also owns a refrigerator working either with electricity or oil. Currently, only the power supply works. In case of power failure, the medical staff transfers all the vaccines kept in the refrigerator in frozen boxes.

This refrigerator could easily work with biogas during power failures. For 1 hour of cut for a refrigerator of 100L, it is necessary to count 0.05 to 0.1m^3 of biogas (ref biboule).
Thus 1m^3 of biogas can maintain the refrigerator during 10 hours

School canteen

The CEG (JUNIOR COLLEGE) of the centre welcomes approximately 500 pupils. There is no school canteen. According to the director, in lean period, a canteen would allow to increase the school attendance, which decreases in these periods. The installation of an AD plant there would allow sensitizing the children. However, it would be difficult to find economic earnings for the maintenance of the system. A small contribution of the parents could be a solution.

Hotels

Some hotels/restaurants use a lot of gas every month to cook. It is possible that one or several hotels build an AD plant to reduce their gas bill. They would take care of the plant and use the gas. It would be a public-private partnership, allowing the use of the gas by people mastering the system, being able to invest for a digester and able to assure the maintenance of the plant. That could be a good solution if it is clear for them that the proposition is economically interesting. The idea is interesting because instead of building a central digester and then make a redistribution of the gas, which is problematic, it would be wastes which would be distributed between several small installations, allowing the treatment of a fraction of MSW.

Public lightening

Conversion in electricity solves the problem of distribution of biogas. Gas benefits to many users indirectly (all the population passing by the centre). However, the municipality does not apparently pay the electricity for the public lighting; it is the national electricity company (Jirama) which cover it. Thus it would not be a source of savings for the community. Furthermore, the conversion in electricity is more difficult technically than the simple use for the cooking.

7. Institutional aspects

	Community vision	Public-private partnership
Use	Public place where cooking fuel or electricity is required	Benefit to the owner of the plant
Ideas	• Hospital • Scholar canteen • Public lightening (example market)	• Hotel who would cook with biogas • Private who would sell electricity
Conditions:	• Association motivated • Formation necessary • Agreement with the municipality for care and management of the plant • Products should generate money to pay maintenance costs	• Private people interested • Formation necessary • Agreement with the municipality for care and management of the OMSW
Advantages:	• Facility profits to many people • Possibility of sensitization on the question of SWM of the all population	• Avoid abandons problems • Management more « direct » and easier
Shortcomings :	• Elevated risks of abandon in case of technical problem, investment needed or low profitability	• Do not profit to the community directly

Whatever the institutional system adopted, the role of the municipality will have to be clearly defined.

8. Financial feasibility

Municipal management of waste is not a "lucrative" activity; however it is possible to limit the costs thanks to valuation. Beyond the environmental and sanitary profits, this section tries to make the sum of the economic profits that would be possible to generate with AD and to compare current spending with those with an AD plant.

a) Costs/profits for the Municipality

The 3 following table present the financial review of current and future situations for: i) the waste management at the moment, ii) the sorting of waste of the municipal bin, iii) a primary collection of sorted waste.

They do not take into account initial investments for an area of sorting or the implementation of a collection. It only considers the daily costs.

Tableau 10: Financial statement for MSWM currently and in the future, after displacement of the dumpsite

Current situation (Dumpsite in the centre)			**future situation** (Dumpsite in Moratsiazo, 6km from centre)		
monthly expenses			monthly expenses		
Sweepers	3	300'000	Sweepers	3	300'000
Location tractor	40000 Ar/week	160'000	Location tractor	20L/100km, 2.4L/drive, 3 drive per week	232'000
Servicing and maintenance		0	Servicing and maintenance		0
Monthly incomes			Monthly incomes		
		0			0
Total		-460'000	Total		-532'000

Tableau 11: Financial statement for a MSWM scenario including the sorting of the waste of the bins

Scenario Sorting of the Municipal bins , dumpsite in Moratsiazo (6km)		
monthly expenses		
salary sweeper / sorting people	sweep in the morning, sorting the rest of the day full time job: augmentation of minimum 30 000Ar	390'000
Tractor	20'000Ar 1 ride to Moratsiazo + 2 small ride to the AD plant	160'000
Maintenance private installation	Maintenance done by the owner of the plant	0
Total expenses		550'000
Monthly incomes		
	depends of the use of gas	
Total Incomes		0
Financial statement		-550'000

There is around 450kg of wastes throw in municipal bins every day. It has been estimated that one person can sort 40kg of waste/hour if a practical and suitable plant is build for it. 3 persons would be sufficient to sort the daily waste.

As said previously, the role of the municipality will have to be clear. The question of fees too: will the municipality furnish for free sorted organic waste to hotels or a community AD plant or should users pay something for the service? Municipality will probably require a fee for the service of sorting or the collection, especially if wastes are given to private.

Tableau 12: financial statement for a MSWM scenario including a door to door collection based on a voluntary engagement with subscription

Scenario Primary sorted collect with dumpsite in Moratsiazo			
monthly expenses			
salary sweeper / collector	3 sweeper /collector + 2 supplementary collector (full time job) – (number of collection agent will depend on the percentage of participation)		650'000
Location tractor	20'000Ar 1 ride to Moratsiazo + 2 small ride to the AD plant		160'000
Maintenance of collection chariots and material			10'000
Total expenses			820'000
Monthly incomes			
	Number of participating households/hotels	Monthly subscription fee	
Subscription Hotel 1 bin 250L Weekly	3	15'000	45'000
Subscription Hotel 2 bin of 250L Weekly	2	30'000	60'000
Gargottes	10	1'500	15'000
Households (25% of the 760 households participating)	190	1'500	285'000
Total incomes with 25% of participation			405'000
Financial statement			-415'000

Subscription fees chosen for calculations:
Hotels/restaurants: 15000 Ar/month for 1 blue can (250L) per week, 30 000Ar for 2 cans and more.
Households and gargottes: 1500 Ar/month.

With these subscription fees, a collection with 15 % of the households and 5 hotels participating would already allow to pay 1 additional person to collect waste.
Collection with 25 % of the households participating would allow paying 2 additional people. If a collection is organized, it has to be source sorted, otherwise expenses would be too elevated (additional salary necessary to separate the waste).

These calculations are approximations, however, it emerges that currently, the municipality spends 460'000Ar per month for sweeping and waste management. If the dumpsite is moved to Moratsiazo, costs will increase by 70'000 Ar / month. If wastes from the bins are sorted in the centre of the village, expenses for waste management would be almost identical to those without valorisation and with the dumpsite far from the village. The AD would allow savings of fuel for transportation to the dumpsite. This money could then be use to increase salaries of the sweepers who would have a full-time job to sweep and collect waste.

If a collection is organized, incomes generated could pay additional collectors and finance maintenance of equipment. With 25% of households participating, the municipality would spend the same sum as currently but with a municipal service of collection.

b) Investment cost

Tables below present investments and period for return on investments for 3 different scenarios.

- The first one it is a 30m3 AD plant with mechanical pre treatment to produce electricity. It is the most expensive and most complex considered system.
- The second is a 15m^3 digester with very simple use: no grinding and the gas is used for the cooking.
- The last one it is a "family" 8m^3 AD plant, with mechanical pre treatment. Gas is used for cooking.

Tableau 13: Example of Investment costs for 30m3 AD plant with mechanical pre-treatment and production of electricity

Example Investment 30m3 AD plant with mechanical pre-treatment and production of electricity				
30m3 AD plant	cost (Ar)	annual costs for maintenance (Ar)	gas produced (m3/jour)	Electricity (kWh)
30m3 floated dome digester	12'000'000		17	33
electrical grinder 3kW	3'000'000			-9
desulfurization	2'000'000			
generator 8kW	4'000'000			
accommodations	2'000'000			
others				
water	X			
Maintenance (5%)		1'150'000		
Total	23'000'000	1'150'000	17	24
daily electricity savings(kWh)				24

A 30m3 digester is suitable if additional material is added as generator and grinder. Thus, investments costs are much higher and maintenance costs too. It could produce about 24kWh every day, which is largely sufficient for the public lightening. Money savings have not been calculated as a precise cost for kWh has not been found and depend strongly of the region and user.

Tableau 14: Example of Investment costs for a 15m3 AD plant without pre-treatment with gas as cooking fuel

Example Investment 15m3 AD plant without pre-treatment with gas as cooking fuel				
15m3 AD plant	cost (Ar)	annual costs for maintenance (Ar)	gas produced (m3/jour)	total daily cooking time (hours)
15m3 floated dome	8'000'000		4	11
Desulfurization	100'000			
Burner				
Accommodations	2'000'000			
Water	X			
Maintenance (5%)		505'000		
Total	10'100'000		4	11

This AD plant would cost approximately 10'000'000 Ar. It would supply daily 10.5 hours of cooking. 189kg of charcoal (at least 1500kg of wood) or 63 kg of gas bottle per month could be saved thanks to the system. For somebody using already 1 in 2 gas cylinder of 9kg weekly, the investment would be paid back in approximately 2 - 4 years.

Tableau 15: Period of return on investment for a 15m3 AD plant without pre treatment with gas as cooking fuel

Period of return on investment 15m3 AD plant without pre treatment with gas as cooking fuel						
	Remark		daily savings [kg]	daily savings [Ar]	Monthly savings [kg]	monthly savings [Ar]
Charcoals savings	1.5kg charcoal = 1m3 biogas 1kg charcoal = 400Ar		6	2'520	189	75'600
Gas bottle savings	1h gas cylinder = 0.2kg 9kg gas cylinder = 50 500Ar		2	11'783	63	353'500
Maintenance (5% of invest ment)	annual maintenance costs from the second year of use				505'000	
Time for return on investment for consumer using:	actual savings			Time for return on invest-ment (year)*		
45 kg charcoal/week (1,5 bag)	18000Ar/week for charcoal **			11.1		
2 cylinders 9kg/week	101000Ar/week for gas			2.1		
30 kg charcoal/week (1 bag)	12000Ar/week for charcoal **			17.5		
1 cylinder 9kg/week	50500Ar/week for gas			4.2		

** Year of maintenance before total return on investment have been taken into account. ** Do not take into account the potential augmentation of coal price*

Tableau 16: Example of Investment costs for a 8m3 AD plant without pre-treatment with gas as cooking fuel

Investment for 8m3 AD plant with pre-treatment and gas as cooking fuel				
8m3 AD plant	cost (Ar)	annual costs for main tenance (Ar)	gas produced (m3/jour)	total daily cooking time (hours)
8m3 floating cover ("all including kit")	1'600'000		2	5
Desulfurization	included			
Burner	included			
Accommodations	500'000			
mechanical grinder	1'000'000			
Water	X			
Total	3'100'000	155'000	2	5

This AD plant would cost approximately 3’000’000 Ar. It is much cheaper than the other pre-sented because the dome is not in metal but in plastic (it is a tarp-balloon). Furthermore in this example, it is sold in "kit" including everything, which reduces strongly the price. However the durability of this system can be lower. A mechanical grinder was added to the scenario to increase the yields. It would supply daily 5 hours of cooking. It would allow saving 90kg of charcoal or 30 kg of gas cylinder per month. For somebody using already 1 gas cylinder of 9kg weekly, it is not possible to reach autonomy in gas but reduce the consumption of gas cylinder to 1/month. For somebody using 1 bag of charcoal / week, the system would be paid back in 6 years. For somebody using more than 3 cylinders of 9kg / month, the time for return on investment would be only 1 and half year.

Tableau 17: Period of return on investment for a 8m3 AD plant kit with pre-treatment and gas as cooking fuel

Period of return on investment 8m3 AD plant with pre-treatment and gas as cooking fuel					
	Remark	daily savings [kg]	daily savings [Ar]	Monthly savings [kg]	monthly savings [Ar]
Charcoals savings	1.5kg charcoal = 1m3 biogas 1kg charcoal = 400Ar	3	1'200	90	36'000
Gas bottle savings	1h gas cylinder = 0.2kg 9kg gas cylinder = 50 500Ar	1	5'611	30	168'333
Maintenance (5% of investment)	annual maintenance costs from the second year of use			155'000	
Time for return on investment for consumer using:	actual savings		Time for return on investment (year) *		
90 kg charcoal/month (3 bag)	36 000Ar/month **		8.6		
3 cylinders 9kg/month	153 000 Ar/month		1.6		
120 kg charcoal/month (4 bag)	13000Ar/week for charcoal **		6.2		
4 cylinders 9kg/month	50500Ar/week for gas, saving of 3.3 cylinders/month, only partial autonomy in gas		1.6		

* *Year of maintenance before total return on investment have been taken into account. ** Do not take into account the potential augmentation of coal price*

In summary, different size of plants are possible/to consider. What is important is the sustainability and suitability of the system. The choice should be decided in function of gas needs and economic viability.

The institutional and financial montage is decisive for the success of this kind of project.

Stakeholders of the village

Population

The population is the main actor for a project of waste management. It is thus necessary to make sure that citizens are motivated to participate. It is also important that they understand that their participation is profitable for everybody (example: improvement of the living environment, evident cleanliness of the village...) Moreover, the sweeper/collection agents…should be « socially recognized » as their job is usefull for the whole community, this meaning a good salary and recognition from population. These are keys factors to motivated citizens. Awareness-raising campaigns should be overtaken.

Volunteers

Within the municipality, volunteers are sometimes gathered for concerted actions. Mrs Lolona is one of the persons in charge for these actions. Furthermore she owns a biogas « home made » system. Thus, she would be a good person to contact to oversee awareness-raising activities for example.

Hotelkeepers

They represent an important entity in the village. Many of them work, on various scales and by various means, for the development of Ampéfy. It is in their interest to preserve the village and surrounding beautiful environment and they are for the greater part conscious of it. They could be a driving force for a project by serving "as example" or by bringing financial contributions more important than households for a waste collection. **Some of them are ready to build an AD plant in their property if municipality distribute OMSW.**

Association 3A

"L' Association des Amis d' Ampéfy" includes about fifteen active members, inhabitants of Ampéfy for the greater part. The association works at the improvement of life conditions in the village. They financed for example the renovation of the health centre, connection to the electricity network of the public high school or did an awareness-raising action on the waste problem by a big collective collection. They could be the right entity to involve for the implementation, the follow-up of such a project.

Amadese association

Malagasy association working for the economic, social and environmental development of the region, based in Ampéfy. It has «for object to realize socioeconomic actions and to carry its support for the implementation, for the management and for the promotion of the local and regional structures". They propose services meeting the needs of the economic growth of regions, the improvement of the conditions and the standard of living of the population and the environmental protection.(Amadese 2016) They could also be an interlocutor of choice for implementation, follow-up of a project.

Foamenzène association

Works in the field of sanitation, particularly against the defecation outdoors (usually abbreviated DAL). The association has several places of intervention, mainly in the district of Soavanandriana. 2 employees are based in Ampéfy. They helped for installations of dry toilets in all the schools of the village. They could also be an interesting interlocutor for implementation and follow-up.

Municipality

The current team is interested in a project and lends to collaborate. However, a waste valorisation project should not be their responsibility because a change of team after election could disrupt the process. The municipality should be involved and participant to produce the necessary municipal by-laws, give « Dina » (local fine) to the peoples who are not respecting the law for waste management, organize awareness raising campaign…

Tools: recently, a **Local Structure of Dialogue** (Structure Locale de Concertation - SLC) has been established. It will constitute a tool so that citizens having requests can send them to the municipality and municipal by-laws can be decided based on these propositions.

But it is important to work with the existing associations of the village. It is a chance that there are presents and for a good basis and visibility of the project, they are necessary. Moreover, their advice could be precious as they live on-the-spot.

Conclusion – Recommendations

The valuation of municipal organic waste by AD is technically feasible and interesting. Ampéfy is a small municipality; it is thus possible to manage the waste of the village with a simple organization. Furthermore, the municipality arranges numerous dynamic actors as associations and hotelkeepers ready to build up a project and there are already 3 AD plants in the village to make sensitive the population. All these elements converge to say that Ampéfy has the potential to become an "experimental" village for valorisation of OMSW.

However, the institutional and financial aspects of such a project are to be deepened. A further study on 2 scenarios should be led. It would allow deciding between a public / private partnership with hotelkeepers using the municipal waste as inputs or a facility profitable for the community and managed by a group of people. The study should help to specify the institutional set up chosen, to establish main actors, the potential investments of each, the role of the municipality and to chose between a collection or a simple sorting of the municipal bins.

The case of Ampéfy is not isolated. The majority of rural municipalities in Madagascar could treat a fraction of their MSW by AD. Only the stakeholders, the waste sources and the institutional and financial aspect have to be study on a case by case basis.

V. Reflection on biogas for rural areas in Madagascar

The idea of diffusing the AD technology in rural area is widespread in many parts of the world. NGOs or private companies offers implementations of small AD plants for families on different economic models in many countries (Eawag 2014; Arti company 2014). Some governments have politics to encourage these initiatives and participate to vulgarisation of AD. China and India are often mentioned as example. In Africa, it is mainly NGOs that finance the initial investment (Soumah 2015; Etc Terra 2012). They present AD as a very suitable solution for the subsistence-farming context that could help the small farmers to get out of poverty. Theoretically, it could reduce deforestation, avoid or reduce expenses for cooking fuel, produce good fertilizer… Moreover, in Africa the climate is favourable on the whole continent. So the question is: why is there no AD plant everywhere in the rural area in Madagascar? Why so many AD plants built in Madagascar have been abandoned (Krieger 2016; CNRIT 2016)Is it really interesting for the people? Which constraints were not considered?

1. Results of a small survey in rural area on cooking habits/interest for biogas

For precise analysis of these results, see "etude socio economique sur la gestion des déchets et le potentiel pour la valorisation des déchets organiques par méthanisation à Ampéfy»

A socio-economic survey was carried out in the village of Ampéfy (as explain in the section IV) but also with 30 persons in the rural surroundings of the village.

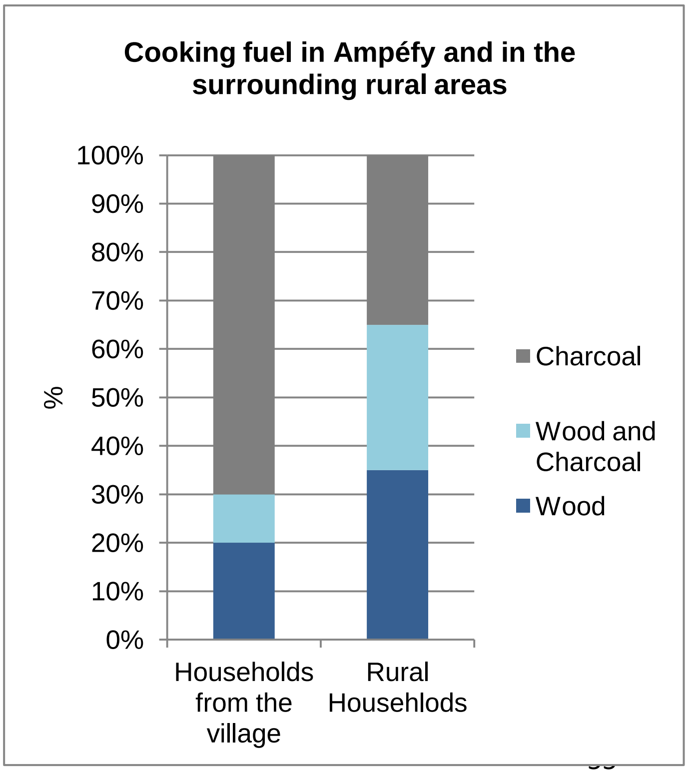

Figure 23: Cooking fuel used in Ampéfy and surroundings areas.

Cooking habits:

Nobody interviewed can afford cooking with gas.

The majority of household from 3 to 5 peoples estimated there consumption of charcoal to 1 bag (30kg) per month in the rural area. They all cook around 3 hours per day (1h/ rice pot).

In the village, the average was a bit higher (1 to 2 bag/month).

In the campaign, people buy the charcoal they can afford and

complete by collecting wood in the neighbourhoods.
Some people even buy the wood as they have to walk too far to collect wood.

Knowledge/interest on biogas:

65,5% have never heard about AD, 34,5% have. About 38% said they would not accept to use this kind of facility.
Often, people who directly reject the system do not have a high level of education. Either they had no arguments to justify this choice or mentioned « cultural reasons ». It is possible to correlate the acceptance with the level of education.

Precision: Before asking questions, the general principle of AD was explained.

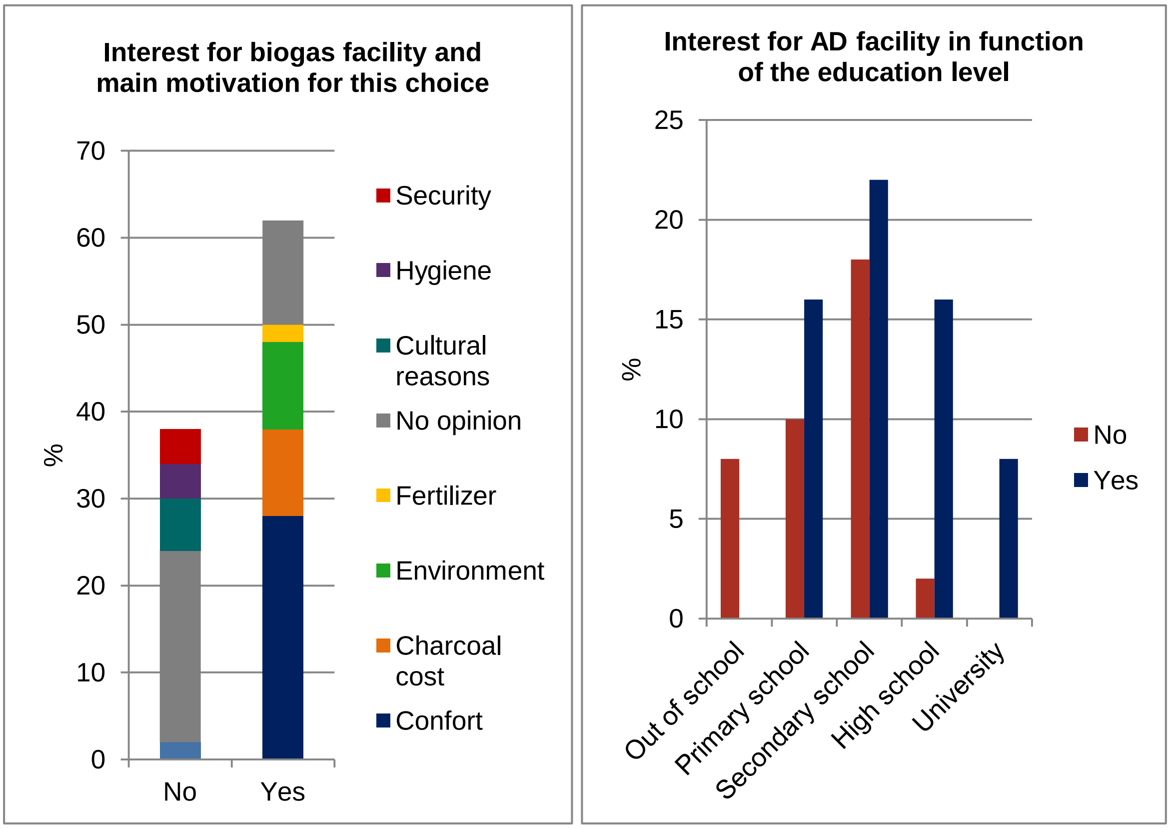

Figure 24: Interest for biogas correlated with the education level and reasons for this interest

The last argument against biogas was the security aspect : cooking with charcoal looks much less dangerous to people who are use to it than cooking with gas, as they do not master how gas works and they just known that it is explosive.

2. Rapid cost and benefits analysis based on the survey and others re-searches

order of magnitude	
average salary [Ar]	130'000
Price for 1 zebu [Ar]	300'000 to 1'000'000

Tableau 18: Summary of the needs and expense for one household for cooking fuel

Needs for **one household**	
Cooking time every day [hours]	2-3
Charcoal	
Quantity of charcoal per day [kg]	1
Quantity of charcoal per month [kg]	30
cost [Ar]	12000
price for 1kg of charcoal [Ar]	400
Wood	
price for 1kg of wood on the market [Ar]	120
Quantity of wood per day, around 2kg/day/person (FAO 2010) [kg]	5-10
Cost [Ar]	free

In Madagascar, the average salary is around 130 000Ar (360 Euros) and many farmers do not earn « cash » money every month. For some household, the spending for charcoal is the main expenditure item.

The following calculations consider the 2 cheapest systems seen in Madagascar. One is « home made », built by the farmer himself with simple material : 250L tank in plastic or metal, 2 PVC pipes for inlet and outlet, one truck inner tube or another 200L-250L tank that fit into the first one (see appendix 2).
The other is the one described in section II, which is too big for one normal household.

The table 19 shows the time necessary to amortize the investment for the 2 types of AD plant. The home made system is not sufficient for one household. For complete autonomy, at least 4 digesters of this type are required.

Tableau 19: time for return on investement for charcoal users and wood users

Digester	price [Ar]	energetic potential			Charcoal users				Wood users			
			feedstock loaded [kg]/day	Cubic meter of biogas produced [m3]/day	Savings of coal [kg]/day	Savings of money [Ar]/day	Current spending for charcoal [Ar]/month	Period for return on investments [years]	Savings of wood [kg]/day	Savings of money [Ar]/day	Current spending for wood [Ar]/month	Period for return on investments [years]
"home-made" tank 250L	200'000	HRT = 30jours	4.2	0.3	0.4	160.0	12000.0	3.5	2-4	0.0	0	No financial amortization possible
Kit 8m3 floating cover digester	1'500'000	HRT = 40jours	56.3	3.8	5.4	2160.0	12000.0	10.4	30-40	0.0	0	No financial amortization possible
							24000.0	5.2				

On the opposite, the floating cover digester is oversized for a household of 4-5 persons. Moreover, to use it entirely, a minimum of 50kg of manure has to be loaded, it is addressed to a family owning at least 3 zebus.

An intermediate volume of digester, measuring between 2 to 3m^3 and processing 15 to 25kg of manure/organic waste per day would be the "ideal" size for one household.
A household consuming 1 bag of charcoal per month would need 3.5 years to amortize a 250L digester which satisfies ¼ of his needs in cooking fuel. It is quite challenging in a country where most of the rural household cannot plan more then month ahead because of their economic insecurity.

3. Discussion

The implementation of an AD facility has to consider several aspects, as showed in the section III (figure 13).

In the rural context, **the technical feasibility has to be insured**, meaning that the household has to generate enough feedstock. This factor restricts already the number of potential household. Not everybody owns cattle or pigs and it is not possible to consider only organic waste as feedstock for 2 reasons: rural household generate very few quantities of waste and recycle almost all the organic waste to feed animals or make compost. Also, the organic waste fraction includes dust and sand swept in the surroundings. These wastes cannot be used as feedstock. Human faeces could also be considered as feedstock but in the cultural context of Madagascar, acceptance will be limited on the highlands and extremely difficult on the coast. Moreover, use of human faeces makes difficult the direct use of digestate as fertilizer while farmers have interest on the fertilizing value of effluent.

The second important point is **the financial aspect**. As shown in table 19, even the smallest AD represent 2 months of salary for a Malagasy. The return on investment is none for somebody collecting wood and last 3 and half years for a household consuming 1 bag of charcoal per month.
Very few farmers can afford an AD plant. For a farmer to invest, he has to be convinced of the "benefit" of the AD technology, meaning that he does not only consider financial aspects but also the environmental one. He has to be interested on bio-fertilizer and be conscious of deforestation problems.

And last but not least, the **sociological aspect**. During the project, 3 AD plants implemented in farmer's family have been visited. All had been paid by NGOs. 2 of them were abandoned. When we ask the reason for this abandon, one said he had to pay a new tarp and had not the money, moreover, the NGO had not explain how to use the system, so he just buried back the digester. The second did not give a real answer. Only 1 system out of the 3 is still in use.
These visits show that the technical aspect is not the only one to consider. The "habits", the routine pattern has to be deeply studied.
In Madagascar, most of the time, children (or women) are responsible for the wood harvest. They go, every day or every week to collect "dead" wood. Sometimes they walk very far away as there is no more wood near the house. Women are also in charge for meals. When the man comes back, the meal is ready. He does not have to take care of that.
An AD plant needs maintenance/loading at least 2 times a week. It changes the habits and many people are not ready for changes of the routines. It is one of the potential explanation to justify why this farmer just stop to use the facility.

If a subsidised biogas plant is installed, most of the time, the man will spontaneously take this responsibility as traditionally women cannot be considered as responsible for technical equipment….But once the plant does not, the woman will go back to fetch wood. Attention should be paid to who in the family is trained to be responsible for the plant.

If AD plants are installed in rural area, only rich farmers could invest. If they do, the maintenance will be assured and the plant will be running as people do not abandon something they paid for.

If AD plants are installed by NGOs for poor rural families unable to invest themselves, an adapted strategy should be established defining who should be in charge in the family, how maintenance should be done and insuring a close monitoring for each plant. No company or NGO is actually proposing such a service in Madagascar.

4. Conclusion - Recommandations

Implementation of AD plants in rural area is theoretically a very good and suitable idea. However, the implementation is not so easy. First reason is that investment costs are high. Secondly because to reach self-sufficiency in gas, the waste needed is more than a normal household production (2 zebus or 6 -7 pig are necessary). This means that it doesn't concern the poorest household.

Working in rural area in Madagascar is difficult for many reasons. Education level is very low, and it is not easy to understand the real needs of the people, their priorities, the fact that they only have short-term visions because their main preoccupation is survival. Investment in an AD plant needs a projection in a medium or long-term vision, which is not simple for a family living in a campaign only on their crops and who do not earn regularly money. People potentially interested have to be convinced of the comfort of gas cooking and the quality of digestate as fertilizer. It is the case of people cooking with gas cylinder for example. It is also the case of people with a higher education level. For all these reasons, small farmers don't seem to be the better "target people" for AD plants in the actual context. Implementation should be done first with people able to invest to avoid abandon and maintenance problems. Then, the technology could be spread, the market would offer more possibilities, and companies or NGOs could propose solids support programs with appropriated strategy for implementation of AD. This would facilitate vulgarisation of the system, leading to changes in mentalities, accessibility of material and knowledge...and rural population could then for sure benefit from AD technology.

VI. General conclusion

Technically, “low tech” AD appears simple, suitable and feasible at different scales and for different social groups in Madagascar, from the small farmer with 3 zebus to the average municipality or hotel. It offers interesting solutions to some of the farmer’s problems as to the municipalities’ concerns.

Apparent simplicity of AD “technology” hides a more complex reality. Indeed, many parameters have to be summed for the effective long-term running of an AD plant, whatever the size. It requires on the same area a sufficient source of waste, minimum financial capacities, motivated people trained for the use/monitoring of the plant, solutions to consume the produced gas and digestate... If one or more parameter is missing, the risk of abandon is great. The example of rural abandon cited in section V, but also of the drying unit in section III are good examples. In the first one the financial and training capacities were failed, in the second one the source of waste was too far from the plant to be an economic and suitable solution.

The experiment carried out during this work has shown the influence of parameters as feedstock or pre treatment on productivity. This shows that AD is not such a basic technology. If it is easy to run an AD plant, yields can vary tremendously depending on the mastering of the process. In our case, yield increase of 1.5 just by limiting the size of inputs.

In order to get facilities operational, technical competences are needed. The experimentation plant as used in this project is interesting to generate data on AD in Madagascar, but also and mainly to train local people (future engineers, technicians...) to master the process. That is why it is interesting for the technology diffusion to have experimentations (and not demonstration) plants, because at this stage, further experiences can be conduct in order to learn more about the process and its adaptation to different contexts.

The valorisation of Organic Municipal Solid Waste by AD is a good option as it brings a decentralized solution for the treatment of 70% of the MSW (and can be combined with composting if quantities of waste are too big). Even the treatment of faecal sludge can be achieved. Inhabitants of villages are asking for a better waste management and sanitation. Municipalities could have a “catalyser” role by promoting implementation of the system. They could do campaign for sensitization of populations to the value of wastes, underlining the importance of sanitation systems.

Each municipality interested should find the financial and institutional set up suitable for its needs and capacities, taking in account the four criteria mentioned above. The potential is huge as almost no rural municipalities in Madagascar have a waste management program, whereas it is part of their responsibilities. Enthusiasm from NGO is understandable as AD has manifold advantages and almost no inconvenient, but as any technical solution, it should be integrated and adapted in each specific social and cultural context. For the time being, based on the existing knowledge, we think that it should be first developed and promoted in structured entities like municipality or schools or hospital. Widespread in all rural household could come as the following step, once AD will be more common in Madagascar and when associated services and strategies will be available.

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VII. Appendix

Appendix 1

Tableau 20: Values resulting from characterization, estimations, literature and survey

Caractérisation	ménage 1	Ménage 2	Ménage 3	Gargotte	Bac	Marché	moyenne
densité [kg/m3]	**375**	**246**	**376**	**271.4**	**315**	**362**	**339.9**
kg déchet/jour/tête	**0.3**	**0.18**	**0.65**				**0.38**
organique [%]	69	98	?	70	69	59	**min 70%**
particule <2cm [%]	20	Résultat pour ménage 2 peu fiables, pas pris en compte	Incompréhension, impossible caractériser en détail	3.4	18.5	29.5	17.9
Plastique [%]	2.3			3.3	3	4	3.2
Papier Carton [%]	4.8			6.4	5	1.5	4.4
Complexes Métal Autre [%]	2.2			1.6	6.5	6	4.1
Remarques	organique min 70% car petite fraction constituée surtout de charbon de bois et cosse haricots						

Sondage	**pourcentage population**	**L/jour/personne**	**kg/jour/pers**	Pour les calculs: 3410 habitants	22.5 sceaux de 10L pour 137 habitants
quantité déchets totale		1.64	**0.56**	**avec estimation 340kg/m3 venant de la caractérisation**	
Tout au Bac	25				
décharge sauvage	?				
gestion autonome	75				
Réutilisation organiques	50			déchets organique=**600kg/m3**	

données nationales	déchets [kg/jour/pers]	densité	taux de collecte
Rapport Banque mondiale"What a waste" 2012 annexe J,L,M	0.8	entre250-500kg/m3	18%
selon AFD Banque mondiale 2012 The economiste (dans doc proparco AFD)	entre 0.5 et 0.9		
selon Source : PUDi-ONE – mars 2006, dans	entre 0.1 et 0.45		

Résultats Sondage + caractérisation	kg/jour/pers	densité	**m3/jour**	**m3/an**	**t/an**	taux de collecte
quantité déchets ménages totale	**0.47**	**339.9**	4.7	1712.1	581.9	
Tout au Bac			1.2	428.0	145.5	25%
décharge sauvage					?	
gestion autonome					436.4	
Organiques dans le bac					**101.8**	
Réutilisation organiques					291.0	

Appendix 2 : examples of homemade plant

Figure 25: "home made" 1m3 plant implemented by an NGO. It is not sufficient for the daily needs of the only women using it.

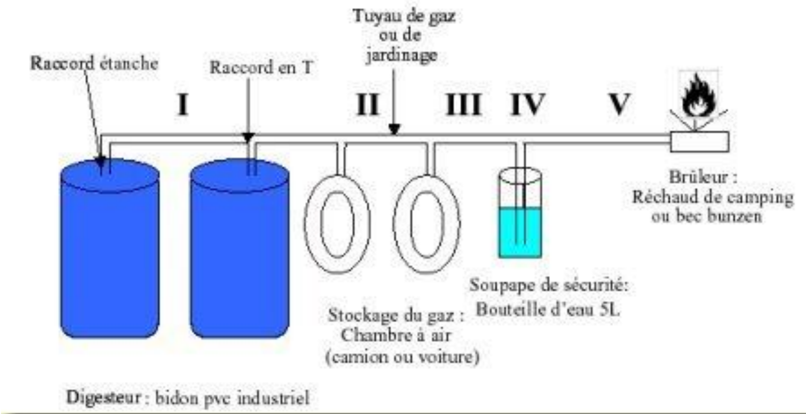


Figure 26: Home made biogas plant using truck inner tube as storage device, source: www.onpeutlefaire.com

Figure 27: Home made biogas plant 250L, source: http://www.instructables.com/id/Biogas-at-home-Cheap-and-Easy/

Figure 28: home made digester with PVC tube as inlet and outel pipe, source:http://myhomehobbies.blogspot.ch/2011/09/home-made-bio-gas-plant.html

Appendix 3 : protocol for laboratory measurements

Protocole expérimental concernant la digestion anaérobie (biogaz) pour des mesures simples et réalisables dans le laboratoire de la sécherie de Moratsiazo

Attention, ces expériences nécessitent l'usage de produits dangereux comme l'hydroxyde de sodium ou l'acide sulfurique. Elles doivent être effectuées par des personnes connaissant les règles d'usage de ces produits et d'un laboratoire en général.

Détermination du % de solide total des intrants ou du digestat

Etant donner que le laboratoire est équipé d'une étuve n'allant que jusqu'à 80°C et la sécherie est équipé d'un four a gaz, le protocol initial (House, 2006) a été modifié.

Prélever des échantillons de environ 100gr des déchets ou autre matière a caractériser. Prendre au moins 5 échantillons à différents endroits du « tas » d'intrants.
Mixer afin d'obtenir le mélange le plus homogène possible (l'idéal est d'utiliser un mixer si il y en a un a disposition). Sinon il est possible de couper/broyer a la main le plus possible.

Pré chauffer l'étuve a 80°C . Choisir des flacons propres en verres ou céramique supportant des températures de 120°C (type bécher). Choisir les bécher de 100mL à 250mL. Peser les flacons à vide (=B en mg)
Insérer les échantillons dans les béchers. Peser à Nouveau (= A en mg) Mettre a l'étuve a 80°C jusqu'à que le poids soit constant (laisser 24h puis peser toutes les 4h environ jusqu'au poids constant). Une fois cela atteint, mettre les échantillons dans le four préchauffé à 105°C et peser régulièrement jusqu'à poids constant. (=C en mg)
Calcul : % solide total $=\left[1-\left(\frac{A-C}{A-B}\right)\right]*100$
A = poids du bécher + échantillon initial [mg]
B = poids du bécher vide [mg]
C = poids du bécher + échantillon sec [mg]
Vs = volume de l'échantillon

Faire une moyenne de tous les échantillons.

Il est possible de faire la même mesure pour le digestat. Il faut prendre 5 échantillons de quelques mL seulement (environ 10mL). Bien mélanger avant de prélever.

Remarque : les échantillons ne sont pas directement mis au four pour éviter les odeurs dans le four. Une fois secs, cela ne pose plus de problème, ni d'odeur ni d'hygiène

Pour plus de détails : Biogas Handbook, House .D, 2006, ISBN 0-915238-47-0 AACR2

Mesure de la qualité du gaz : ratio CH_4/CO_2 (House, 2006)

Methode 1 : mesure très « simple »

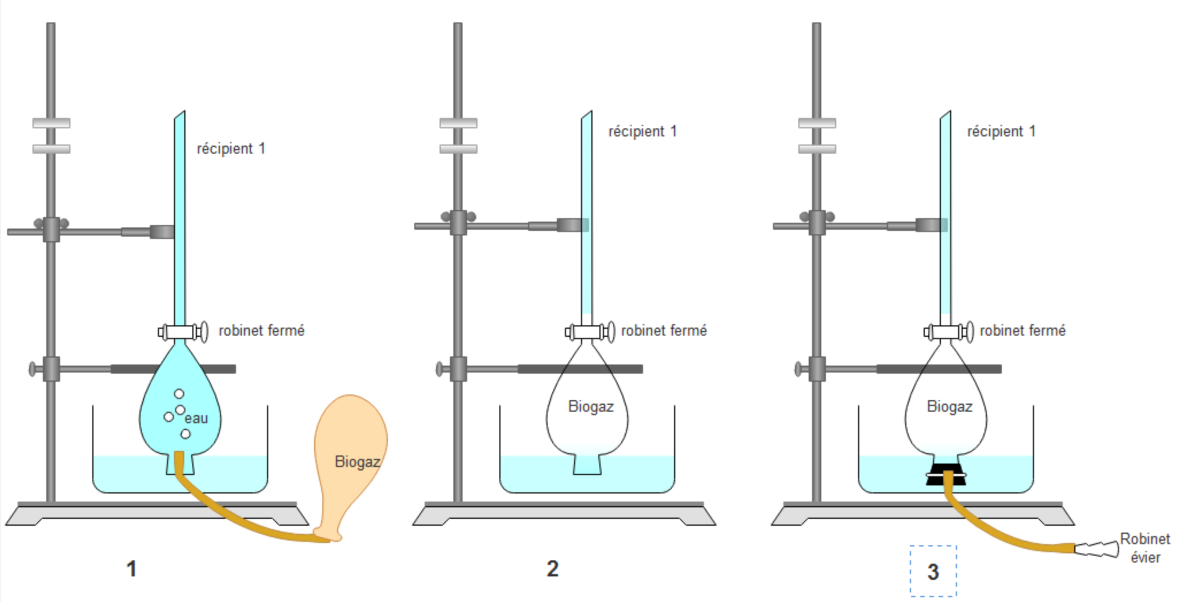
Matériel : - NaOH
-seringue de 10 ou 20mL
-ballon de baudruche pour prélever du biogaz
-eau distillée
Pour cette expérience qui utilise de la soude, il faut porter des gants, des lunettes de sécurité. Il peut être bien d'avoir a disposition du vinaigre afin de l'appliquer en cas « d'éclaboussures » et pour traiter la solution alcaline jusqu'à pH neutre une fois utilisée.
Méthode :

- Préparer une solution très concentrée en NaOH. Par exemple une solution 10M en mettant 40gr de
  soude dans 100mL d'eau distillée. (si la soude est de bonne qualité il est possible de préparer une solution moins concentrée, il faut juste que la soude soit largement en excès, un minimum de 2M est souhaitable).
- Prélever du biogaz dans un ballon de baudruche à l'aide du compresseur (prendre le tuyau de sorti du compresseur, y mettre le ballon de baudruche en tenant bien pour éviter les fuites, allumer le suppresseur pour gonfler le ballon de biogaz). « Entortiller » le ballon pour garder le gaz dedans.
- Mettre le ballon sur une seringue (en évitant les fuites la encore). Prélever 6mL de gaz avec la seringue de 10mL, « ré-entortiller » le ballon et prélever rapidement 4mL de solution de soude. Boucher l'extrémité de la seringue avec le doigt et secouer la seringue. Pendant quelques minutes, alterner les secousses avec des compressions dans la seringue (toujours en bouchant bien avec le doigt attention !).
- Au bout de quelques minutes, le volume de gaz aura diminué. Cela représente le CO_2 qui était présent dans le gaz et qui a réagit avec la soude. Le volume de gaz restant, c'est du méthane.
- Faire cette expérience au minimum 3 fois par échantillons pour avoir une moyenne.
  Calcul : % de CH_4 = $100 - (\frac{Vi-Vf}{Vi} * 100)$
  Vi = volume initial de gaz prélevé (exemple 6mL)
  Vf = volume de gaz après manipulation
  Les résultats, si le biogaz brûle, devraient se situer entre 45% et 70% (ref biboule+handbook). Au-delà
  de 70% cela veut dire que la mesure n'a pas fonctionné (le biogaz ne dépassant jamais 70% de CH_4). Ce
  la peu venir de la qualité de la soude, de la concentration de la solution…

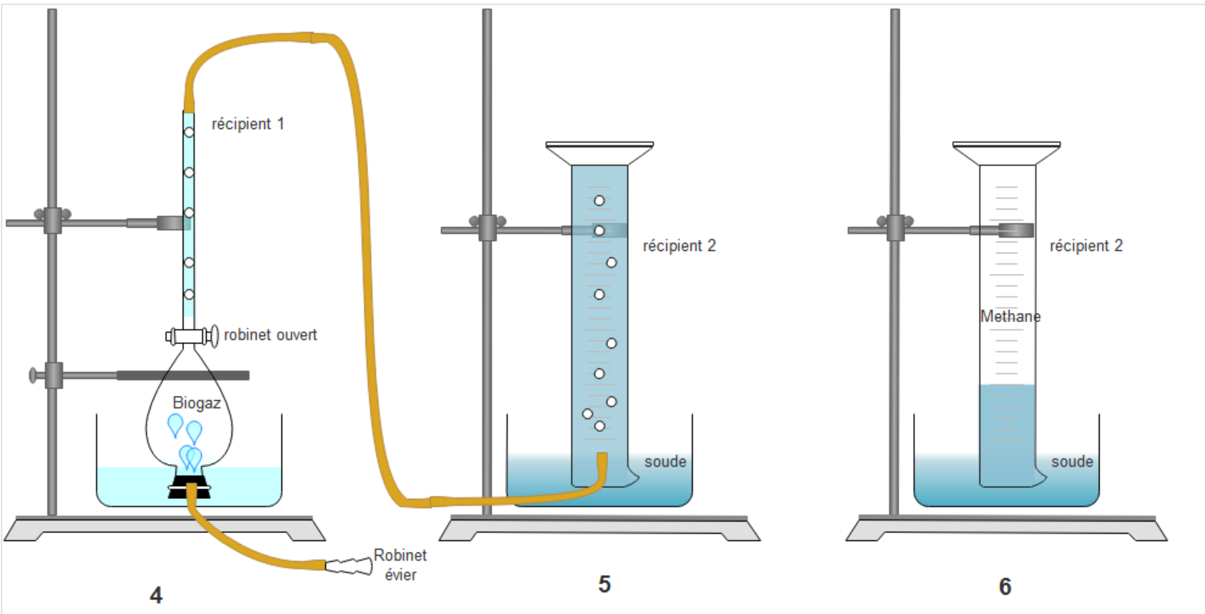
Méthode 2 : méthode avec déplacement de l'eau

Des essais ont été faits avec un montage plus complexe de déplacement d'eau. Cependant les résultats étaient les même qu'avec la méthode de la seringue alors que la manipulation est bien plus compliquée. La qualité de la soude achetée est probablement responsable de ces « mauvais » résultats. Si de la soude pure est achetée alors il sera intéressant de réessayer cette deuxième méthode qui devrait être plus précise. La méthode 2 est basée sur le même principe que la méthode 1 mais le gaz prélevé va « buller » doucement dans la solution de soude. Ci-dessous : montage de la 2ème méthode.

- Remplir d'eau a ras bord un réservoir (récipient 1) de volume X connu ayant un robinet. Le retourner dans un récipient rempli d'eau. Faire buller le volume X de biogaz (méthode du ballon de baudruche comme dans la méthode 1 pour prélever le biogaz) (image 1).
- Remplir de solution saturée en soude à ras bord un réservoir gradué (récipient 2). Le retourner dans un récipient rempli de la même solution (image 5).
- Brancher un tube rempli d'eau au robinet du récipient 1 et le coincer dans le récipient 2 retourné. (image 4 a 5)
- Prendre le bouchon fixé à un tube avec du silicone. Le connecter au robinet de l'évier, le remplir d'eau et ensuite le fixer sur le récipient 1. (image 3)



- Ouvrir un peu le robinet du récipient 1 puis lentement ouvrir le robinet de l'évier. L'eau du robinet doit déplacer la biogaz dans le récipient 2. (image 4 et 5).Le mieux est de faire cela lentement afin que le CO_2 réagisse avec la soude. Quand tout le gaz a été déplacé, fermer vite le robinet du récipient 1 et de l'évier pour ne pas trop diluer la solution alcaline.



- Laisser le montage une nuit (plusieurs heures). Agiter parfois si vous passer a côté (image 6).

- Pour finir, lire le volume dans le récipient 2. C'est le volume de CH_4. Suivre la même formule que dans la méthode 1 pour le calcul. Si il n'y a pas de cylindre gradué, prendre un récipient, faire un trait au stylo du volume de gaz final puis le calculer en le remplissant d'eau.

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Méthode aussi expliqué dans : Master Thesis, Biogas measurement techniques and the associated errors, Prakash Parajuli, 2011
(https://jyx.jyu.fi/dspace/bitstream/handle/123456789/36767/URN%3ANBN%3Afi%3Ajyu-2011100611506.pdf?sequence=1)

Mesure du Carbone Inorganique Total par le titrage en 4 points de *Kapp (Buchauer, 1998)*

Ce titrage permet de déterminer la quantité de carbone inorganique (TIC en anglais, approximé comme l'alcalinité) et d'acides gras volatiles (VFA en anglais, abrégé par A) de l'échantillon. Le ratio A/TIC donne des informations sur la stabilité du processus de digestion anaérobie. Si ce ratio est stable, alors le processus est stable. Si ce ratio augmente, cela indique généralement une augmentation d'acides gras volatils produits, signe d'instabilité. Le ratio est normalement inférieur à 1.

Matériel :

- Solution d'acide sulfurique 0.05M
- pH mètre calibré
- filtre seringue 0.45uM
- agitateur magnétique ou cuillère avec un mélange constant

Prélever le digestat à analyser. Il faut un volume suffisant pour que l'électrode pH soit toujours sous la surface du liquide (environ 16-20mL). Filtrer le digestat avec des filtres seringues 0.45uM (la filtration est nécessaire pour ne pas endommager l'électrode à pH avec des impuretés solides).
Le pH de la solution est mesurée.

Attention, les volume a ajouter sont souvent minime, quelques gouttes, procéder avec une pipette ou seringue très précise et ajouter goutte a goutte !

La solution est titrée lentement en ajoutant goutte à goutte la solution d'acide sulfurique jusqu'à ce que le pH 5 soit atteint. Noté le volume ajouté (= A1)
Ajouter de la solution d'acide sulfurique jusqu'au pH 4,3. Noter le volume ajouté (= A2).
Ajouter de la solution d'acide sulfurique jusqu'au pH 4. Noter le volume ajouté (= A3).

Calculs :

$$\text{Alcalinité} = A * N * 1000 / Ve$$

Alcalinité (mmol/L)

A = volume ajouté pour passer du pH initial à 4.3 = A1 + A2 (ml)

N = normalité = 2 * molarité pour H_2SO_4 en mmol/L

Ve = volume initial de l'échantillon

$$\text{VFA = acides gras volatils} = 131340 * N * B / Ve - (3.08 \cdot Alc) - 10.9$$

VFA (mg/L d'acide acétique équivalent)

B = volume ajouté de pH 5 à pH 4.3 = A2 + A3

N = normalité = 2 * molarité pour H_2SO_4 en mol/L

Ve = volume initial de l'échantillon

Alc = alcalinité

$$\text{Ratio VFA/Alc = ratio A/TIC} = \frac{VFA\,[\frac{mgl}{L}]}{Alc\,[\frac{mgl}{L}]}$$

Pour calculer le ratio, les 2 résultats doivent avoir la meme unité. Le carbone inorganique total (Alc) est

convertit en mg/L d'équivalent $CaCO_3$. Comme une molecule de $CaCO_3$ réagit avec 2 H^+ et 1 H_2O:

$2H^+(CaCO_3 + H_2O$-------Ca_{2^+} + HCO^{3-}+ OH^-).

On multiplie Alc par la moitié de la masse molaire de $CaCO_3$

Alc [mg/L] = Alc[mmol/L] * 50,042

**Remarque : si la solution d'acide est trop concentrée pour votre échantillon (trop petits volume à ajouter pour changer le pH), diluer là 10 fois, il faut ensuite prendre ce changement en compte dans la formule de calcul (exemple si vous diluez 10 fois, N n'est plus égal a 0.1 mais a 0.01). Au contraire, si il faut ajouter trop de solution d'acide pour un changement de pH, diluer votre échantillon et prenez en compte ce facteur dans la formule (exemple : diluer 10 fois : vous multiplierez le résultat de VFA ou « Alc » par 10).*

Pour plus de details sur la methode, voir : *A comparison of two simple titration procedures to determine volatile fatty acids in influents to waste-water and sludge treatment processes*, Buchauer 1998 disponible sur : http://www.araconsult.at/download/literature/1998_comparison_titration_procedures_buchauer.pdf (consulté en mars 2016)

Ou alors: Anaerobic digestion, Lohri.C, 2009: https://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/SWM/Anaerobic_Digestion/Lohri_2009_Appendix.pdf