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Aboubakary BAMBA

Technical feasibility Study of biogas production from biodegradable municipal solid waste in Abidjan: Case study of households in Yopougon

Defended on 26/09/2018 Before the Following Committee:

Chair	**Prof. Chakib SELADJI**	(Tlemcen University)
Supervisor	**Dr. Christophe GBOSSOU**	(CRERA)
External Examiner	**Prof. Zaki SARI**	(Tlemcen University)
Internal Examiner	**Dr. Abdellah BENYOUCEF**	(Tlemcen University)

Academic year: 2017 – 2018

DECLARATION

I, Aboubakary BAMBA, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Aboubakary BAMBA 05/09/2018

(Student) (Signature) (Date)

Certified by:

Dr. Christophe GBOSSOU 13/09/2018
(Supervisor) (Signature) (Date)

ABSTRACT

Despite all the efforts made in the management of household waste in Abidjan, uncontrolled deposits are increasing in the streets of the city. The most vulnerable areas are those with a low-income population. It is in this that the study will look at a rural style zone located in the municipality of Yopougon along the Ebrié lagoon called BEAGO. The village habitat consists of group of several households among which the study focused on a concession composed of 22 households. The survey carried out in the area revealed a daily production of **108.8 kg** of household waste for all the targeted zone of which **63.03 kg** constitutes on average the organic fraction intended for the production of biogas. The production of biogas takes place through the so-called anaerobic digestion process (absence of oxygen) which results into a mixture of gases contained in the biogas, the most important are methane and carbon dioxide. In the case of the study area, the use of basic equations made it possible to estimate the daily biogas potential of organic waste to be collected at **10.88 m^3** taking into account the physico-chemical characteristics of the waste used as the humidity, the volatile solids and solid fixed, density also. This biogas potential will produce an energy of **65.26 kWh per day** that could be converted into electricity or for cooking in the households concerned. To contain, the quantity of substrate available over a period of hydraulic retention time estimated at **30 days**, it requires a reactor with a capacity of **9.80 m^3** surmounted by a floating gas tank of capacity **6.53 m^3** using the principle of KVIC (2007) depending on the technology chosen. Also the energy produced will allow to retain the use of **101.05 kg** for all the concession is **4.56 kg** per household. Finally, the use of bio waste produced in the households of this small community results in the safeguard of the environment with a CO_2 emission of **6.78 tons per year**, knowing that the first environmental advantage comes from the use of the methane contained in the organic waste when discharged to open surfaces thus become a potent greenhouse gas harmful to the environment and the sharp reduction of wood for cooking will significantly reduce the risk of diseases especially lung.

Key words: Anaerobic Digestion; biogas; humidity ; volatile solids; hydraulic retention time; CO2 emission

RESUME

Malgré l'ensemble des efforts consentis dans la gestion de déchets ménagers à Abidjan, les dépôts anarchiques ne cessent de s'accroitre dans les rues de la ville. Les zones les plus vulnérables sont celles dotées d'une population à faible revenus. C'est en cela que l'étude se penchera sur une zone de style rural située dans la commune de Yopougon au large de la lagune Ebrié appelée BEAGO. L'habitat du village étant constitué de concessions composées de plusieurs ménages parmi lesquelles l'étude s'est orientée sur une concession composée de 22 ménages. L'enquête effectuée dans la zone a révélé une production journalière de **108.8 kg** de déchets ménagers pour toue la concession dont **63.03 kg** constitue en moyenne la fraction organique destinée à la production de biogaz. La production de biogaz s'effectue à travers le procédé de la **digestion** dite **anaérobie** (absence d'oxygène) qui donne en résultat un mélange de gaz contenu dans le biogaz dont les plus importants sont **le méthane** et le **dioxyde de carbone**. Dans le cas de la zone d'étude, l'utilisation des équations de bases a permis d'estimer le potentiel journalier en biogaz des déchets organiques à collecter à **10.88 m^3** en tenant compte des caractéristiques physico-chimiques des déchets utilisés comme le taux d'humidité, le taux de solides volatiles et solides fixes la densité également. Ce potentiel en biogaz permettra de produire une énergie de **65.26 kWh** par jour qui pourrait se convertir en électricité ou pour la cuisine dans les ménages concernés. Pour contenir, la quantité de substrat disponible sur une durée de temps de rétention hydraulique estimée à **30 jours**, il faut un réacteur d'une capacité de **9.80 m^3** surmonté d'un tank de gaz flottant de capacité **6.53 m^3** en utilisant le principe de KVIC (2007) en fonction de la technologie choisie. Aussi l'énergie produite permettra de retenir l'utilisation de **101.05 kg** pour toute la concession soit **4.56 kg** par ménage. Enfin, l'utilisation du bio déchets produit dans les ménages de cette concession résulte la préservation de l'environnement d'une émission de CO_2 de **6.78 tons par an** sachant que le premier avantage environnement vient déjà de l'utilisation du méthane contenu dans les déchets organiques lorsqu'ils sont déchargés a des surfaces ouvertes ainsi deviennent un puissant gaz à effet de serre nocif pour l'environnement et la forte réduction de bois pour la cuisine réduira considérablement les risques de maladies surtout pulmonaires.

Mots clés : Digestion anaérobie ; biogaz ; taux d’humidité ; taux de solides volatiles ; temps de rétention hydraulique ; émission de CO_2

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ABREVIATIONS

°C	Degre Celsus
AD	Anaerobic Digestion
BNETD	Bureau National d'Etudes Techniques et de Developement
C/N	Carbon to Nitrogen
CH_4	Methane
CIE	Compagnie Ivoirienne d'Electricite
CO_2	Carbon dioxyde
EfW	Energy from Waste
GDP	Gross Domestic Product
GHG	GreenHouse Gas
H_2O	Water
HRT	Hydraulic Retention Time
IPP	Independent Power Producer
kg	Kilogramme
kWh	KiloWatt hour
MJ	MegaJoule
MSW	Municipal Solid Waste
MWh	MegaWattHour
NCV	Net Calorific Value
ORL	Over Loading Rate
PRONER	Programme National d'Electrification Rurale
RGPH	Recensement General de la Population et de l'habitation
SDG	Sustainable Developpement Goals
SODEXAM	Societe d'Exploitation et de Developpement Aeroportuaire ,Aeronautique et Meteorologique
SOTRA	Societe de Transport Abidjan
SRT	Solid Retention Time
TS	Total Solid
UN	United nations
UNDP	United Nations Development Programme
VFA	Volatile Fatty Acid
VOC	Volatile Organic Compounds
VS	Volatile solid
WtE	Waste to Energy

CHAPTER 1: INTRODUCTION

1.1. GENERAL INTRODUCTION

Changes in the climate were accepted for the first time as a major problem on a global scale in 1979, during the first climatic conference organized in Geneva by the World Meteorological Organization. From this time on, the development policies of countries around the world were taken into account in their planning the safeguarding of the environment in order to reduce the threat that arises as a result of climate change.

In addition, providing access to clean and affordable energy has constituted a huge challenge especially for developing countries. The awareness of new challenges, particularly concerning the environment (climate warming, exhaustion of resources, increase in the greenhouse effect), should bring us closer not only to one more rational use of energy but also of an optimization of the energy processes towards renewable energies.

In the face of the ever-soaring population in developing countries there needs to be a renewed focus on meeting their energy needs in a sustainable way. Within the sub-Saharan African region, there is prevalent widespread use of fossil fuel for meeting the energy needs in the countries, this use of energy from finite and conventional sources will in the near future constitute a huge challenge given the current trends. In response to this impending energy crisis and the problems of pollution, it is imperative and urgent to adopt new effective and inoffensive energy sources for the environment. Renewable energies have the advantage of being available in unlimited quantity. Their exploitation is a means of meeting the energy needs while preserving the environment. These forms of energy generate only little even waste or polluting emissions (Ortega, 2015). One of the principal forms of renewable energy is energy obtained from the biomass, particularly biogas. Biogas comes from animal or vegetable organic matter fermentation in the absence of oxygen, it is composed in its greater part by methane and carbon dioxide (Poulleau, 2002). The process making it possible to obtain biogas is called the anaerobic digestion which falls under the technology of the biomethanisation.

The biomethanisation using of the process of anaerobic digestion started in 1776 for the first through the report carried out by VOLTA A. on gas released on the marshes. After a couple of years (1787), A.L. LAVOISIER gave it the name “gas hidrogenium carbonatrum" but the term of "methane" was proposed and confirmed in 1865 in 1892 by an international congress of chemical nomenclature. Since then this technology is used as option of liquid and solid waste processing. Historically, biogas made great strides in the developed countries which collected it through the treatment of waste waters and regarded it as a no-claims bonus on the energy production and country in the process of development which on the other hand gave it an important place in their deficit in the energy production which presented a high cost. Biogas obtained was intended for the kitchen and also for heating in the rural areas starting from waste of animals. These last decades recorded a strong growth of the production of biogas throughout the world. In 2006, in China, up to 18 million households profited from the commissioning of small systems of organic digesters in rural area with a biogas potential estimated at 145 billion m^3 of biogas for all China while in India 5 million households profited from it. The figure below shows evolution of the worldwide production of biogas these last decades:

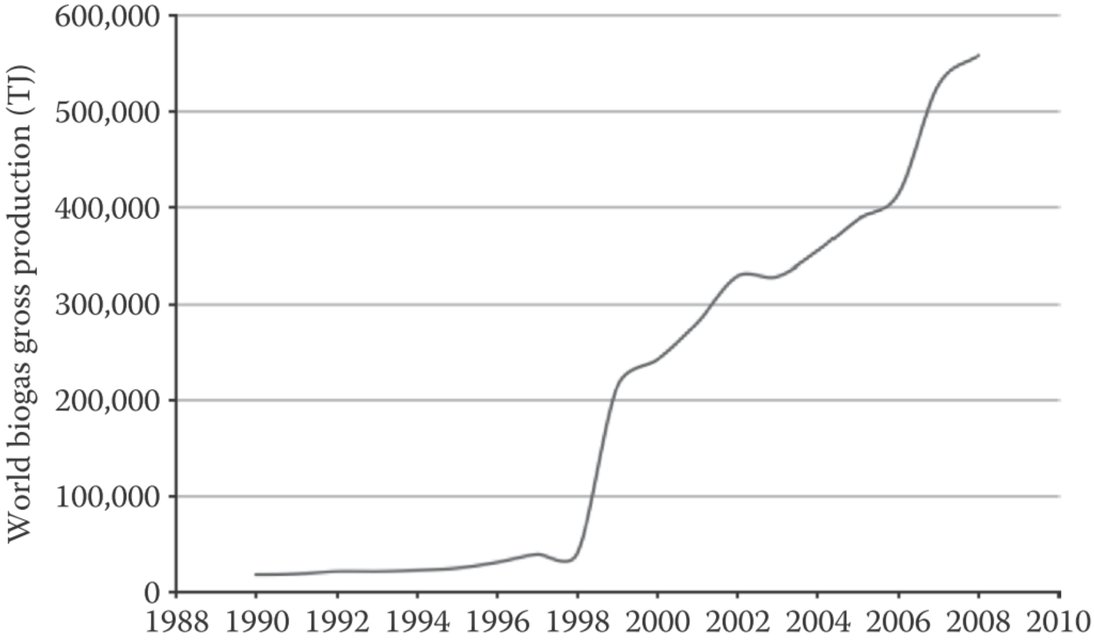


Figure 1.1: Historical biogas gross production (Source: UNDP, 2012)

The graph shows that the production knew a boom starting from 1998 which marks undoubtedly the implication of several of the world in the production of biogas and especially the great powers as indicated on the figure below:

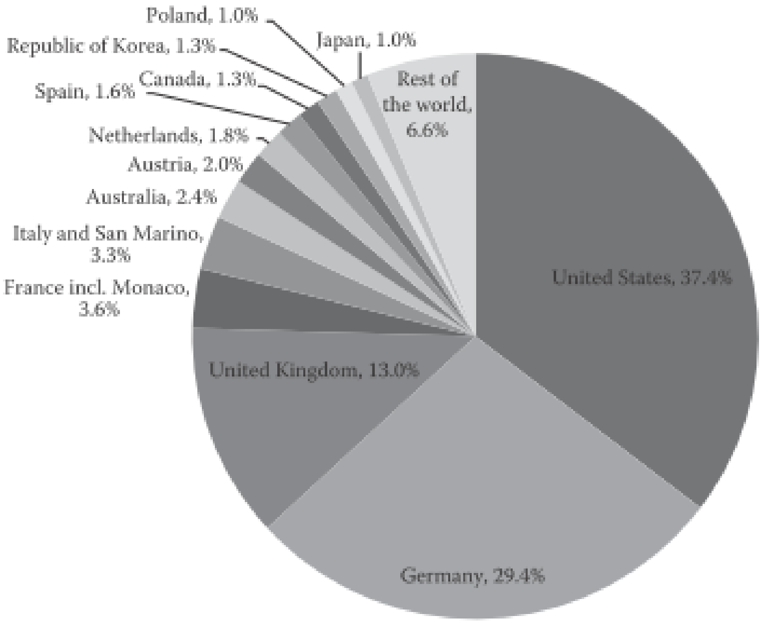


Figure 1.2: Worldwide biogas generation distribution by country, 2008. (From UNDP 2012.)

The ECOWAS Centre for Renewable Energies and Energy efficiency (ECREEE) suggests that the power supply of West Africa can be based up to 54% on renewable energies in 2030, including the hydroelectricity (ECREEE, 2015). Most country within ECOWAS fixed a target of a use from 10% to 20% of renewable energy (except hydroelectricity) in 2020 and 2030 respectively.

Africa has an abundant potential of biomass in the form of organic residues of origin vegetable or animal, agricultural, agro-industrial and urban, which is theoretically sufficient to produce the complementary bioenergy needed in the energy mix to satisfy the total/national demand of electricity. Approximately 850 million people cook and heat their dwellings using traditional hearths and of simple stoves which burn biomass (wood, manure of animals and crop waste products) and coal in sub-Saharan Africa. There exist possibilities of using the biomass available sustainably.

With regards to Ivory Coast, to face the challenge of sedentary elimination of waste in the economic capital, Abidjan was equipped, since 1965, with a controlled landfill with open sky. Former studies carried out by Adjiri and Al (2008) revealed that this landfill is an important source of production of biogas, and that this biogas is primarily made up of CO_2 (26.8 %) and CH_4 (62 %). These two gases are greenhouse gases which contribute to the total warming of planet. In addition, methane takes part in the greenhouse effect on a level 21 times larger than that of CO_2 (Above and Al, 2008). The collecting and the consumption of this would thus reduce its rejection in the atmosphere by transforming it into carbon dioxide and steam. This consumption will then have favourable effect on the Earth (Our planet, 2006).

1.2. PROBLEM STATEMENT AND JUSTIFICATION

Biogas, a mixture of carbonic gas and methane is a fuel gas which comes from organic matter, vegetable waste or animal waste in a medium in rarefaction of air called anaerobic digestion. This anaerobic digestion is the result of the natural or controlled microbial activity. It is a gas rich in methane, but also in halogenous products (chlorine, fluorine) difficult to treat coming from the decomposition of plastics and the presence of toxic wastes (bogus of detergent, batteries…), this is all the more-true when the sorting of waste was badly carried out. Moreover, methane is 21 times more harmful as greenhouse gas than CO_2.

The landfills produce biogas spontaneously because fermentable waste is regularly deposited there. The period of emission can be evaluated on several tens of years, initially at a rhythm growing, then decreasing. The process can be accelerated by humidifying the matter, in which case the potential of production can be recovered between 5 or 10 years.

The town of Abidjan much like other urban areas in sub-Saharan Africa, has seen an exponential increase in its population as well as a development of the socio-economic activities. The corollary which results from this is the increase in the production of solid waste and the complexification of the types of solid waste, more difficult to treat. The district of Abidjan for this purpose, obtained a landfill allocation which receives the waste collected through all the locality of Abidjan for a better control and to have a good visibility on the width of the estimate resulting from the production leaping from waste. This landfill is situated on a site of 35 ha located at Akouédo. Unfortunately, force is to note that the excessive production of waste in comparison with the capacity of the landfill of Akouédo leaves important bad management of received waste.

Moreover, when waste is put in landfill, the biodegradable fractions break up in the landfill and produce over there gases and lixiviat produced in the landfill. If it is not collected, the gas contributes considerably to the greenhouse effect since it is composed mainly of methane gas of which the effect on the climate change is worth 21 times that of carbon dioxide. Thus the knowledge of the potential of production of biogas of waste will make it possible to protect the environment by the installation from a collecting system, which on the one hand will contribute to the reduction of emissions of the olfactive and/or toxic substances and the limitation of the greenhouse effect related to the presence of methane and carbon dioxide and on the other hand to ensure the safety of the site because methane, less dense than the air, circulates underground while following the cracks and goes back to surface or accumulates in cavities and its presence then creates fire hazards and explosions.

About the situation in Yopougon, the waste context is affected by the poor management which leads to reckless disposal in the township. In fact, the waste produced in the households is supposed to follow the different steps of waste management in the town which is pre-collection, main collection and landfilling. However, this management meets a break in certain parts of the town that are mainly characterized by the social condition and poor incomes of the population. Those criteria lead to other problem oriented towards energy supply. Yopougon population like most of people in the country don’t care to the possibility to produce energy by clean and renewable due to the poor share of renewable energy in Cote d’Ivoire that the energy context is leaded by natural gas and hydropower. The possibility of conversion of waste to energy is so unknown with the population of Yopougon however could cover an important part in their energy need. Therefore, biogas production from the waste generated in the households could be an initiation of population to integrate the relevance of renewable source to fulfil their energy needs.

1.3. RESEARCH QUESTIONS

The application of the technology of production of biogas through anaerobic digestion remains, in certain in countries like Ivory Coast, a mystery which let run several interrogations with the essential ones which arise are:

- The application of biogas production through anaerobic digestion feasible within sight of the context of Ivory Coast which let arise the question such as is it really working?
- The feedstock used for AD, is it enough and available to ensure biogas production?
- Which advantages does one draw from this alternative from the point of view of valorisation for waste on the plane environment?

1.4. RESEARCH HYPOTHESIS

Taking into consideration the context of Ivory Coast with regards to domestic waste management, one could believe that any alternative would be a solution to slow down the negative repercussions on the populations. The idea of the use of this waste for the production of biogas comes at the right moment as a good alternative in the policy from valorisation of waste. The studies that have been conducted in other regions could enable us to establish if the technology is feasible within sight of the abundant availability of biofuel resource. Also, the facility of application of the process of anaerobic digestion predicts a good performance of technology for the context of the town of Abidjan. Finally, this project promoting the use of waste as an energy source has a great environmental advantage considering waste will be new destinations other than the discharges which lack good treatment thus leave the populations under the influence of the suffocating odours.

1.5. OBJECTIVE AND AIM

1.5.1. Main objective

This study aims at clarifying the feasibility of the production of biogas starting with household wastes. Indeed, this technology is new and has not matured and would need to be better exposed in order to introduce it into the policy of valorisation of household wastes in the town of Abidjan, the economic capital city. Incidentally this city which is observed with the greatest quantity of waste in Ivory Coast due to its high population, the level of modernization marked by its economic activities and the lifestyles of the population.

1.5.2. Specific objectives

- To determine the characteristics of the waste produced in the commune of Yopougon in order to define the methanogenic potential of the whole of this waste deposited at the landfill.
- To develop a technical solution allowing the collection of the methane potential at beneficial ends for the population what would return to the proposal of a biodigester likely to contain this need for use of waste.
- To show the economic and environmental benefit of this alternative. It will be a question of defining the undergone environmental impacts which will be seen raised through the adoption of this project.

1.6. RELEVANCE OF THE STUDY

Seeing that this option of waste to energy through anaerobic digestion is new for the context of Cote d'Ivoire and the low use of renewable energy in the country, this study can be considered as an initiation of Ivoirian to the valorisation of their own garbage through energy production especially in the production of biogas. Therefore, this study will lead to:

- The provision of an alternative and sustainable solution to waste management in Cote d'Ivoire.

- Additional source of gas supply to the population seeing that the country sometimes faces a scarcity of gas for cooking.
- The contribution to socio-economic development of Cote d'Ivoire by ensuring a secure and reliable gas supply especially in the rural area around the municipality of Yopougon.
- Sensitization on renewable energy awareness campaigns in Cote d'Ivoire and in the role of renewable in ensuring the country's energy security.
- Improvement of the share of renewable energy in Cote d'Ivoire as well as serve as a tool to investors and attracts government attention for significant investment in the renewable energy sector.
- It will also add on the current knowledge on renewables and climate change mitigation in the country and the world at large through achievement of 9 of the SDGs as proved by many studies.

1.7. SCOPE OF THE STUDY

This study will manly focus on waste to energy production especially the production of biogas from municipal solid waste of Yopougon. Such a study requires the knowledge of the context of the country in the term renewable energy in general and the reality found in Yopougon specifically. As the topic is linked to the use of the waste or trash produced in Yopougon, it is important for us to know the stream of waste management in the area in order to show the real impact of our study in that way. By the way, the main focus will be on the households as indicated in the study title that leads to know the waste context in the most vulnerable households in the poor management of waste in the township.

CHAPTER 2: LITTERATURE REVIEW

2.1. OUTLOOK OF COTE D'IVOIRE

Key information about Cote d'Ivoire:

Key indicators	**Amount**
Population (Millions inhabitants)	23.70 (2016)
Urban population % of total	54.2 (2015)
Rural population % of total	45.8 (2015)
Electrification Rate (%)	55.80 (2016)
Surface Area (sq. km)	322 642
GDP (Billions USD)	36.37 (2016)
GDP per Capita (USD)	1 526.20 (2016)
CO2 Emission (Metric tons per Capita)	0.49 (2016)

Table 2.1.1: Key information about Cote d'Ivoire

2.1.1. Geography of Cote d'Ivoire

Ivory Coast is a country of western sub-Saharan Africa. The country is approximately square in shape with an area of 322 462 km2. It borders Liberia and Guinea in the west, Mali and Burkina Faso in the north, Ghana in the east, and the Gulf of Guinea (Atlantic Ocean) in the south. The country lies between latitudes 4° and 11°N, and longitudes 2° and 9°W. Around 6 4.8% of the land is agricultural land, Arable land taking up 9.1%, permanent pasture with 41.5%, and permanent crops occupying 14.2%. Ivory Coast has as political capital Yamoussoukro located in centre of the country and economic capital Abidjan located in the southern of the country.

Figure 2.3: Geographic Location in the world and its map

2.1.2. Energy sector profile

2.1.2.1. Current status of electricity sector

The current electricity production in Ivory Coast is 1,632 MW with a net output of the interconnected network of 8.152 GWh, and the number of people having access to electricity estimated at 55.8% in 2011, (Compagnie Ivoirienne d'Electricité , 2014). True that the Ivorian power sector is thus one of the best in the under region, but he knows from recent years of financial difficulties mainly due to high production costs, the strong growth in demand for electricity and character fixed the selling price of electricity posing on the Ivory Coast shortage of risk in electric energy. The real problem in the electricity sector is the low level of population's access to energy services is factors that limit the level of development. With a population density of 72.2 inhabitants / km² (World Bank, 2015)electricity demand in future years will be very high. Now the power sector today offers a balance between supply / demand precarious. Indeed, over the decade 2000-2009, given the socio-political crisis in Ivory Coast, this led a significant deficit on production behind many time shedding in 2010. If nothing is done, the same load shedding phenomenon may continue on the future decades. The easy access of the population to modern energy services remains a priority for all the countries of West Africa especially the Ivory Coast. There is hope because the biomass is still more than 57% of the energy balance.

To ensure energy security in Ivory Coast in order to provide the population with affordable energy to all at lower cost and preserving the environment, several actions were identified implementation are:

• The National Rural Electrification Program (PRONER 2020) began in 2014, a cost of about 600 billion for the electrification, by the end of 2016, more than 2,012 villages of 800 inhabitants and all villages of more than 500 men in 2020. This will have the effect of raising the national recovery rate 43.3% in 2014 to 95% in 2020 (Elisée.B, 2015).

• Investment of CIPREL up to 225 billion CFA franc to increase its output of 111 MW by the end of the year, so production will increase from 432 MW to 543 MW (Issouf, 2014).

• The installation of the American group Contour Global, which will install a thermal power plant of 330MW to 300 billion. (Jeune Afrique, 2012)

• Construction on the Soubré hydroelectric dam of 275 MW with an investment of 330 billion FCFA. Consequently, domestic production should be around 2000 megawatt in the end of 2016 will double to 4,000 megawatts by 2020. (Jeune Afrique, 2012)

To ensure the same energy security, the Ivory Coast of Africa will construct the largest biomass plant. It will especially to the huge potential of green energy in the Ivory Coast. One of the first agricultural giants and cocoa producer in the world (about 35% of world harvests). The Ivory Coast has one of the largest biomass deposits in Africa, estimated at 12 million tons per year, according to figures provided by the SIFCA group. (Jeune Afrique, 2014)

The ambition of the Ivorian government that 15% of its electricity is generated from biomass in 2020. (Jeune Afrique, 2014)

2.1.2.2. Electricity demand

Electricity demand is increasing in recent years especially with the growing demographics 1.91 percent in 2015 (Banque mondiale, 2015). Also with a rate of access to electricity 55.8 percent, the Ivorian government must increase its production to ensure its place on the train to the emergence 2020 (Banque Mondiale, 2015). For those doing the Ivorian government wants to continue financing mechanisms based on public-private partnerships. In this context, the government is also committed to restore the financial equilibrium of the electricity sector in Côte d'Ivoire and strengthen its investment capacity. This will of the state is reflected in the Strategic Action Plan developed by the Minister of Petroleum and Energy of Côte d'Ivoire. The use of independent producers allows coping with a growing demand. Of more than 1500 MW of new projects that Côte d'Ivoire plans to 2020 service, thermal and hydraulic power plants developed by private developers account for about 85% (CI-Energies, 2013). The new Master Plan for 2013-2030 Production in progress will explore all potential sources of production in Côte d'Ivoire. In addition, the new code of electricity being adopted reflects the will of opening to private by defining the new regulatory framework of the sector for future investments. Finally, the need for energy induced by large projects (mining, for example) will also increase. So there is a strong potential for private production of electricity in Côte d'Ivoire.

2.1.2.3. Electricity distribution

After the privatization of the electricity sector in 1990, the Ivorian government decided to create the Ivorian Electricity Companies (CIE), and concedes to this new structure the national utility generation, transmission, distribution, export and import of electric power - with the aim of ensuring the financial recovery of the sector. In 2014, according to data of the Ivorian Electricity Companies (CIE), the Ivorian electricity network is as described in the table below:

This figure below shows the national and international electricity transmission network of Ivory Coast.

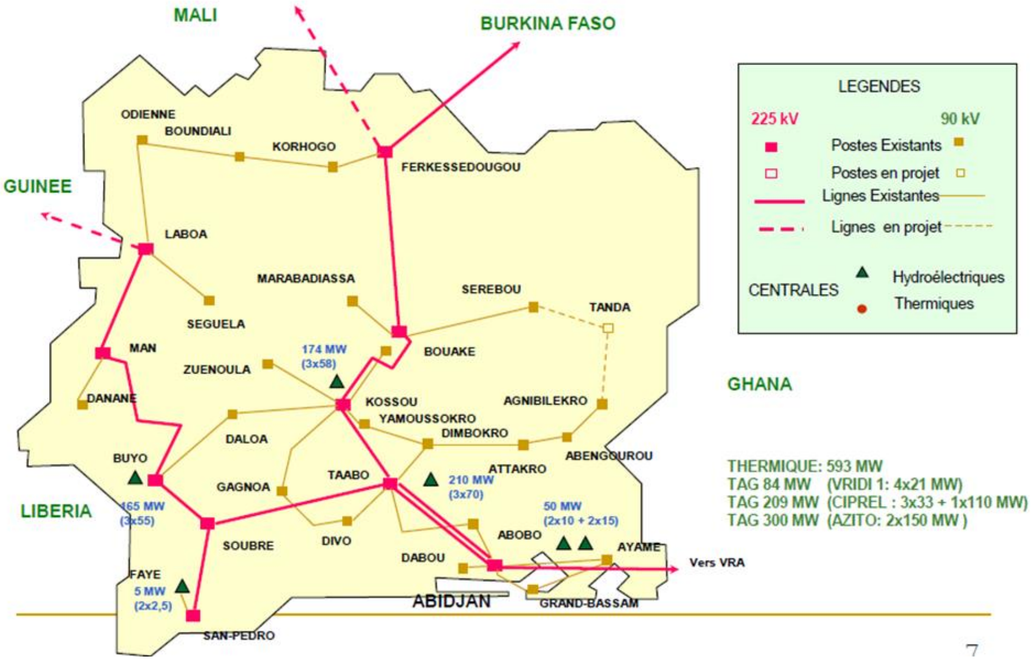


Figure 2.2: Electricity Transmission in Ivory Coast

2.1.3. Renewable energy resources

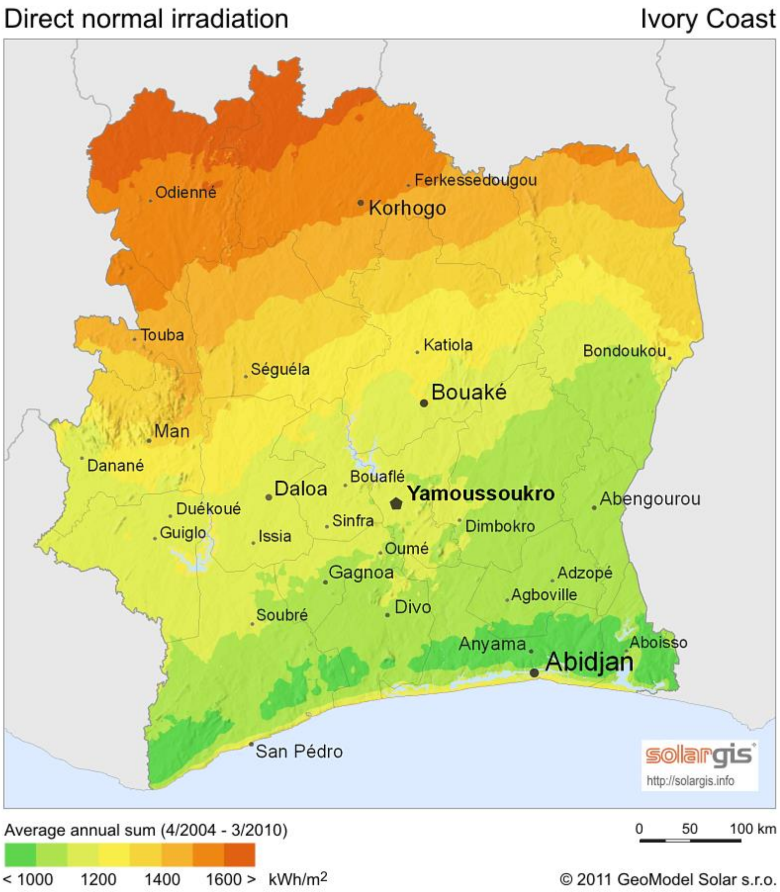
Government statistics and data on resources and market potential are still limited, but it can be assumed that Cote d’Ivoire has strong potential for hydroelectric, solar energy and biomass installations. According to existing data, the country’s suitability for wind and geothermal power generation is comparatively low.

2.1.3.1. Solar Energy

Cote d’Ivoire receives abundant solar energy. The solar potential in the country ranges from 2.0-4.5 kWh/m2/day, with an average of six hours of sunshine a day, indicating moderate potential for this form of energy. The annual potential for photovoltaic installations is 10,325 TWh. (RECP, 2014)

The action plan foresees the completion of at least 12 pilot projects in rural areas. (RECP, 2014)

Figure 2.3: Insolation representation in Cote d'Ivoire



Source: (GeoModel Solar s.r.o, 2011)

An average of 5000 kWh / m^2 in the region of south Abidjan , 4736 KWh / m^2 in the Bouake and Korhogo and 5342 kWh/m^2 in the north of the country (Benjamin, 1994).

2.1.3.2. Hydropower

The Ivory Coast has a technical hydropower potential of 1847 MW. (Komenan, 2008).

2.1.3.3. Bioenergy (Biomass)

As with most African countries, biomass is the most common energy source and it provides about 75 per cent of energy requirements, especially for domestic purposes and for small businesses. Fuel wood is mainly obtained from natural forests, savannah woodlands, bush land and tree plantations, among others. Forested land covers 32.7 per cent of the country (World Bank, 2015d), an area of about 6.38 million hectares. Agro-industrial residues, crops and plantations represent a readily available form of renewable energy and are already being used in some agro-businesses and sawmills (REEEP, 2012). Biogas from household waste is being experimented with in Abidjan.

The production of bioethanol using feedstock from maize, sugarcane and sweet sorghum is also being explored. It is estimated that in the northern part of Côte d'Ivoire, about 120 ktoe per year is available from bagasse (the fibrous by products of extracting sugarcane or sorghum juice) (REEEP, 2012).

2.1.3.4. Wind Energy

Ivory Coast has an average wind speed of 4.8 m /s to 6 m /s at 10-15 meter. This speed is considered insufficient for wind power generation. (AFHON Humanity and nature, 2014).

There are no specific wind data available besides those for civil aviation compiled by the Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM). These measurements, taken at 12m above the ground, range on average from 1-2m/s. San Pedro on the southwest coast and Korhogo in the north have recorded wind frequencies of 20-35% for wind speeds above 6m/s. Wind speeds in Bouake in central Cote d'Ivoire and Touba in the west are greater than 4m/s, with frequencies of 20-45%. Two **wind power** projects, in Touba and Korhogo, are under consideration. (RECP, 2014)

2.1.4.General energy policy

2.1.4.1. Key success factors and limitations

Overall Côte d'Ivoire's experience of using the private sector for electricity generation is a positive one. Several key success factors emerge from this experience. First of all, it should be noted that payments to IPPs, which are collected by CIE, are secured by a law governing funding allocation in the Ivoirian electricity sector, with payments to IPPs prioritised in the management of financial flows. This arrangement has continued to function even in a crisis situation, thus allowing IPPs to continue to supply the power and energy necessary to cover demand. The purchasing of the generated energy is governed by take-or-pay contracts1, which guarantee the private producer sufficient revenues to make the project profitable, in accordance with the business plan produced as part of the feasibility study. Finally, IPPs enjoy attractive tax incentives – in the form of tax exemption on their trading profits for several years – as well as various preferential customs tariffs.

2.1.4.2. Diversifying the sector

The Ivoirian government has made plans to decrease dependence on natural gas in the future while this resource will stay the main in power generating for longer period, by increasing hydropower capacity and developing renewables. However, short-term energy policies are centred on the natural gas sector. There have been many initiatives to expand capacity in thermal power plants, and minimal work has been done in the hydro and renewables sector.

Recently the government has expressed a desire to increase large hydro capacity; however, there are many environmental and social risks associated with these types of projects that often obstruct the process. Côte d'Ivoire has significant potential in other renewable energy though, including wind, solar, biogas, and mini-hydro. Beyond small-scale projects, there has been little effort to develop this potential, which is in part due to the lacking regulatory framework for renewable energy.

Overall, Côte d'Ivoire's dependence on natural gas for thermal power production places unsustainable pressure on the electricity sector. On the positive side though, there are many opportunities for foreign investors in the energy sector, particularly in renewables, as there is an apparent gap between demand projections and existing supply.

2.2. GENERAL TREATMENT METHODS OF SOLID WASTE

Sustainable waste treatment is concerned with management of waste to ensure that the society is not adversely affected by it but will bring about a benefit on a continuing basis. One of the key factors in sustainable waste treatment is to separate the waste into organic and non-organic waste. This will also facilitate identification and separation of hazardous waste. The organic waste is generally used for landfill, composting or incinerating. The initial step in waste treatment is to manage the waste. This will entail transformation of waste so that it could be dealt effectively. The transformation of waste will benefit in many ways. Firstly, it will improve the efficiency of solid waste management system. Secondly it will help to recover reusable and recyclable material. Thirdly it will facilitate recover products to convert to energy.

2.2.1.Thermal Treatments

Energy is stored in chemical form in all MSW materials that contain organic compounds, i.e. everything except metals, glasses, and other inorganic materials. The combustion of these compounds can generate electricity and steam and recover energy.

2.2.1.1. Incineration

Incineration is defined as the chemical reaction of oxygen with organic materials, to produce oxidized compounds accompanied by the emission of light and rapid generation of heat is a disposal method in which solid organic wastes are subjected to combustion to convert them into residue and gaseous products. The process disposes waste by converted it to residues and gaseous products by subjecting it to combustion. Incineration of bio solids is the most common thermal process; however, it's potential for energy recovery is underused. In this process, the bio solids are burned in combustion chamber supplied with excess air oxygen (O2) to form mainly carbon dioxide (CO2) and water (H2O), leaving only inert material (ash). This process is used to dispose of hazardous waste. The thermal treatment of waste could convert the waste material into heat, gas and ash. The energy content of waste products can be harnessed directly by using them as a direct combustion fuel, or indirectly by processing them into another type of fuel. The heat energy could be transformed to other forms of useful energy such as electricity through a gas or a steam turbine which results in converting waste to energy. This process reduces the volumes of solid waste to 20 to 30 percent of the original volume. Incineration and other high temperature waste treatment systems are sometimes described as thermal treatment. Incinerators convert waste materials into heat, gas, steam and ash. Waste-to-Energy (WtE) or Energy-from-Waste (EfW) is broad terms for facilities that burn waste in a furnace or boiler to generate heat, steam or electricity. The amount of energy that can be obtained strongly depends upon the water content of the biomass. Potential environmental problems related to sludge incineration are the emissions of pollutants with the exhaust gases to the atmosphere and with the quality of the ashes.

2.2.1.2. Gasification

Gasification involves partial combustion of a carbonaceous fuel so as to generate combustible fuel gas rich in CO, hydrogen and some saturated hydrocarbons, principally methane. The waste materials are heated to high temperature in an oxygen deficient environment in a sealed high pressure vessel. The waste is converted to solid, liquid and gas products. The gaseous and liquid products could be combusted to produce energy. The cost of this process generally outstrips the benefits (Shabaneh, et al., 2011).

2.2.1.3. Pyrolysis

Pyrolysis is a process of splitting thermally unstable organic substances through a combination of thermal cracking and condensation reactions in an oxygen-free atmosphere, into gaseous, liquid, and solid fractions. It is a thermal treatment process in which the sludge (or biomass) is heated under pressure to a temperature of 350–500 °C in the absence of oxygen. In this process, the sludge is converted into char, ash, pyrolysis oils, water vapor, and combustible gases. Some portion of the solid and or gaseous products of the pyrolysis process are incinerated and used as heating energy in the pyrolysis process. Several kinds of modifications are available depends upon the equipment used and the applied operating conditions that are applied (Shabaneh, et al., 2011)

2.2.2.Biological treatment

In this section, the focus will be only on ***anaerobic digestion***. It will be relative to the different outline about the process of anaerobic digestion and the results gotten through it.

2.2.2.1. Overview of anaerobic digestion (AD)

Anaerobic digestion is a natural biological process that uses microorganisms to degrade organic matter in the absence of oxygen. In the technical systems of anaerobic digestion, the degradation takes place in specially designed reactors or chambers. The required environmental conditions, such as moisture content, temperature and pH levels, are measured and monitored within the reactor to optimize biogas production and rates of decomposition of waste. In a technical system of digestion of organic matter separated at the source of municipal solid waste, the digestion process occurs over a period of two to six weeks.

The most important product of the anaerobic digestion process is probably biogas because it can be used as fuel and thus provides a renewable energy source. Biogas consists mainly of methane (CH4) and carbon dioxide (CO2), but it can also contain significant concentrations of hydrogen sulphide (H_2S) as well as trace amounts of siloxanes and volatile organic compounds (VOCs). The solid or semi-solid materials that remain once the process of anaerobic digestion is completed are called the digestate, while the liquid from the digester is called effluent.

2.2.2.2. Different Phases of Anaerobic Digestion

2.2.2.2.1. Hydrolysis

Complex molecules (large protein macromolecules, fats, cellulose and starch) are converted into simple sugars, long-chain fatty acids and amino acids. Polymers are converted into monomers and oligomers. Hydrolysis is catalysed by the enzymes excreted from the bacteria. The rate of hydrolysis depends on the complexity of the feedstock, carbohydrates convert quite rapidly, whereas raw cellulosic waste is converted slowly (Ostrem and Themelis 2004). The main reactions and bacteria are the following (Al Seadi et al. 2008):

$$\text{lipids} \xrightarrow{\text{lipase}} \text{fatty acids, glycerol}$$

$$\text{polysaccharide} \xrightarrow{\text{cellulase, cellobiase, xylanase, amylase}} \text{monosaccharide}$$

$$\text{proteins} \xrightarrow{\text{protease}} \text{amino acids}$$

The hydrolysis reaction is given in Equation 2.1

$$C_6H_{10}O_4 \rightarrow C_6H_{12}O_6 + 2H_2 \qquad \textit{(Equation 2.1)}$$

2.2.2.2.2. Acidogenesis or fermentation.

Bacteria convert the products of hydrolysis into volatile fatty acids (VFAs; mainly lactic, propionic, butyric and valeric acid), acetates, alcohols, ammonia, carbon dioxide and hydrogen sulphide, as shown in Equations 2.2 and 2.3

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \qquad \textit{(Equation 2.2)}$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \qquad \textit{(Equation 2.3)}$$

2.2.2.2.3. Acetogenesis.

Further digestion produces acetic acid, carbon dioxide and hydrogen via the routes shown in Equations 2.4 through 2.7

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \qquad \textit{(Equation 2.4)}$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \qquad \textit{(Equation 2.5)}$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \qquad \textit{(Equation 2.6)}$$

$$2HCO_3^- + 4H_2 + H^+ \leftrightarrow CH_3COO^- + 4H_2O \qquad \textit{(Equation 2.7)}$$

2.2.2.2.4. Methanogenesis.

Methane, carbon dioxide and water are produced by acetotrophic (primary), hydrogenotrophic and methylotrophic bacteria (Abbasi et al. 2012; Al Seadi et al. 2008). The main reactions and bacteria are the following:

$$\text{acetic acid} \xrightarrow{\text{methanogenic bacteria}} \text{methane} + \text{carbon dioxide}$$

$$\text{hydrogen} + \text{carbon dioxide} \xrightarrow{\text{methanogenic bacteria}} \text{methane} + \text{water}$$

Detailed reactions occurring during methanogenesis are given in Equations 2.8 through 2.11

$$2CH_3CH_3OH + CO_2 \leftrightarrow 2CH_3COOH + CH_4 \qquad \textit{(Equation 2.8)}$$

$$CH_3COOH \leftrightarrow CH_4 + CO_2 \qquad \textit{(Equation 2.9)}$$

$$CH_3OH + H_2 \leftrightarrow CH_4 + H_2O \qquad \textit{(Equation 2.10)}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \textit{(Equation 2.11)}$$

Other important side reactions are given in Equations 2.12 and 2.13:

$$CH_3COO^- + SO_4^{2-} + H^+ \rightarrow 2HCO_3 + H_2S \qquad (Equation\ 3.12)$$

$$CH_3COO^- + NO^- + H_2O + H^+ \rightarrow 2HCO_3^- + NH_4^+ \qquad (Equation\ 3.13)$$

A simplified generic equation for the entire process is shown in Equation 2.14:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \qquad (Equation\ 2.14)$$

The schematic below describes the different phases that occur in biogas formation during the anaerobic digestion

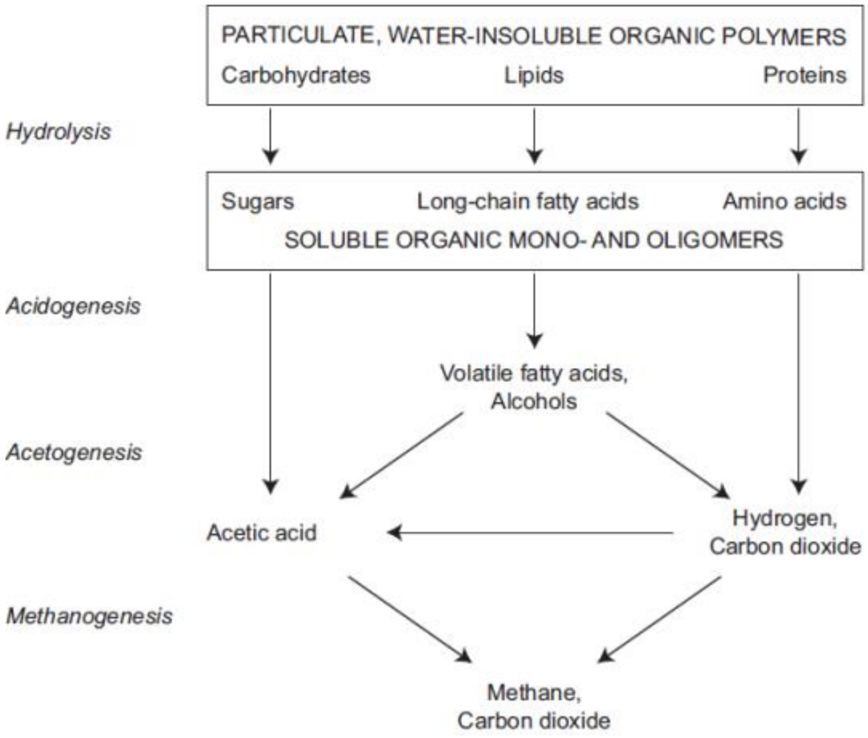


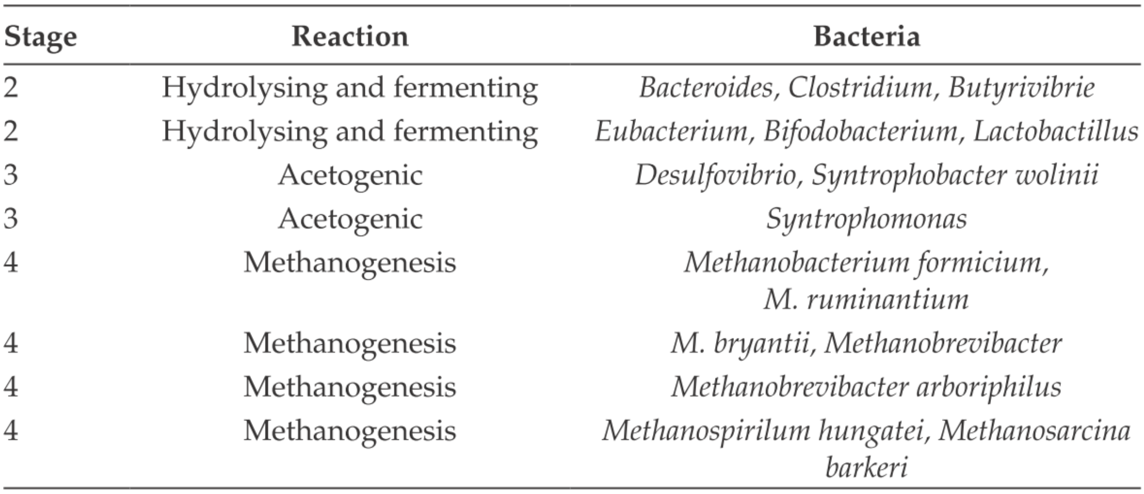
Figure 2.44: Conversion steps of Anaerobic Digestion

2.2.2.3. Bacteria

The presence of adequate bacterial colonies is essential for efficient digestion. Optimal sources of bacteria include animal manure, slaughterhouse wastes and sewage. For this reason, reactors may be seeded with these materials. There are three groups of bacteria involved in anaerobic digestion, as shown in Table 2.2.1.

Facultative anaerobes such as Streptococci and Enterobacteriaceae also take part in the hydrolysis and fermentation (Weiland, 2010). Although most of the bacteria involved in the process are strict anaerobes such as bacteriocides, clostridia and bifidobacteria (Weiland, 2010), strictly speaking, it is only the final methanogenic stage that is truly anaerobic; other cellulolytic, acidogenic and acetogenic bacteria are aerobic or facultative (Abbasi et al, 2012). Methanogenic bacteria occur naturally in deep sediments or in the rumen of herbivores (Ostrem et al, 2004).

Table 2.2.1: Microorganisms involved in AD



Stage	Reaction	Bacteria
2	Hydrolysing and fermenting	*Bacteroides, Clostridium, Butyrivibrie*
2	Hydrolysing and fermenting	*Eubacterium, Bifodobacterium, Lactobactillus*
3	Acetogenic	*Desulfovibrio, Syntrophobacter wolinii*
3	Acetogenic	*Syntrophomonas*
4	Methanogenesis	*Methanobacterium formicium, M. ruminantium*
4	Methanogenesis	*M. bryantii, Methanobrevibacter*
4	Methanogenesis	*Methanobrevibacter arboriphilus*
4	Methanogenesis	*Methanospirilum hungatei, Methanosarcina barkeri*

Source: (Abbasi and Al., 2012)

2.2.2.4. Factors Affecting Biogas Production

The most important factors to consider when choosing a biomass feed for anaerobic digestion biogas production are the total solids content, percentage volatile solids, carbon to nitrogen ratio (C/N) and biodegradability of the feedstock. The biogas yield is most strongly a function of volatile solids, organic composition and bioavailability. Gas yield is also a function of the hydraulic and solids retention times, pH, temperature of fermentation, loading rate, inhibitory effects of substrate compounds and intermediate products (e.g. ammonia, VFAs, hydrogen sulphide), toxicity of any feed or reaction products, degree of mixing/agitation and the presence of any pathogens (Abbasi et al, 2012). The effects of each parameter are discussed below.

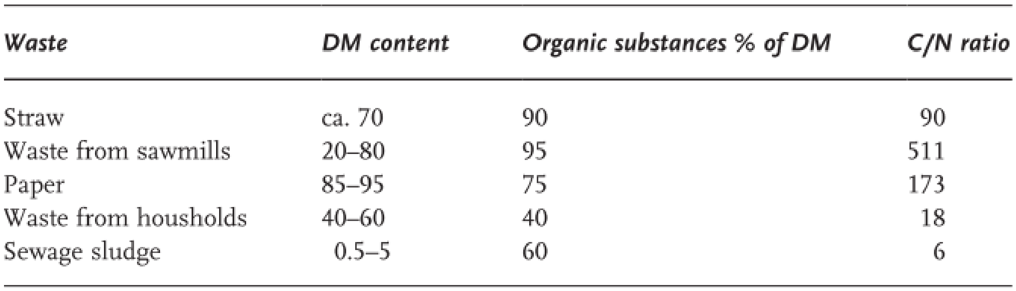
2.2.2.4.1. Solids content and dilution

Solids should be diluted as needed to form an appropriate slurry that can be stirred and allows for gas to flow upwards, but not too thin that particles settle. Each value is reactor specific, but generally 10% to 25% solids.

2.2.2.4.2. Ratio Carbon to Nitrogen (C/N)

A carbon to nitrogen ratio between 20 and 30 is typically optimal. If the ratio is too high, nitrogen is rapidly consumed by methanogens for protein formation and insufficient nitrogen remains to react with leftover carbon material. If the ratio is too low, nitrogen is liberated and accumulates as ammonia, which increases the pH and exerts a toxic effect on methanogenic bacteria. To maintain an optimal C/N, materials can be mixed as each material has its own inherent C/N.

Table 2.2.2: C/N ratio of organic wastes



Waste	*DM content*	*Organic substances % of DM*	*C/N ratio*
Straw	ca. 70	90	90
Waste from sawmills	20–80	95	511
Paper	85–95	75	173
Waste from housholds	40–60	40	18
Sewage sludge	0.5–5	60	6

Source: (Abbasi and Al., 2012)

2.2.2.4.3. pH value

The optimal input pH value is between 6 and 7. Initially, during digestion, the pH decreases and then increases as the reaction proceeds due to ammonia production. When methane production stabilises, the pH is typically 7.2 to 8.2. Methanogenic bacteria prefer a neutral to slightly alkaline environment and cannot survive at a pH of less than 6 (Ostrem et al. 2004). Running a digester on plant material in which the digester operates in batch mode may require the addition of lime for pH adjustment.

2.2.2.4.4. Temperature

Large-scale anaerobic digestion is generally mesophilic, with less thermophilic and much less psychrophilic digestion. Thermophilic digestion is generally more efficient than mesophilic digestion, with a faster digestion rate and consequently smaller digester, but it is more difficult to control, the bacteria are rarer and so typically need to be seeded into the reactor, investment costs are higher and it requires extra energy inputs to maintain the required temperature. Psychrophilic anaerobic digestion is very rare due to the extremely slow rate of digestion at such low temperatures.

2.2.2.4.5. Loading rate

The organic loading rate is a measure of the biological conversion capacity of the system. It determines the amount of volatile solids that a system can tolerate. Overloading quickly leads to system failure through inadequate mixing, increased VFA content and decreased pH.

2.2.2.4.6. Retention time

The duration of contact in the digester of organic material (substrate) and microorganisms (solids) needed to achieve the desired degradation is the retention time. Reactor efficiency increases and necessary reactor volumes are reduced as the retention time required is lowered. Achieving low substrate retention times requires high simultaneous microorganism (solids) retention time. Hydraulic residence time (HRT). Time that an organic material spends in a digester from entry to exit Solids residence time (SRT or ST). The duration of time active microorganisms spend in the digester. ‘Solids’ is used to denote microorganisms in a digester; however, this is not a precise term because most digester feed contains suspended solids, not necessarily made up of live biomass. It is only the volatile solids (VS) content that is involved in anaerobic digestion, non-volatile or ‘refractory’ organics are not. In high solids digestion or solid feed digestion, ‘solids’ is not meant to denote microorganisms

The relationship between HRT and SRT, and the importance of the ‘food to microorganism ratio’ (F/M), is such that the ratio of the quantity of substrate to the quantity of bacteria available to consume that substrate (the F/M) is the controlling factor in all biological treatment. The only way to keep the F/M adequately low, whilst reducing the HRT (increasing efficiency) and keeping the SRT high, is to find a way to pass the substrate through quickly and for the microorganisms to pass through much more slowly

2.2.2.4.7. Toxicity

Mineral ions, especially of heavy metals and detergents, inhibit normal bacterial growth. Small amounts of minerals such as sodium, potassium, calcium, magnesium, ammonia and sulphur stimulate bacterial growth but higher concentrations are toxic. Heavy metals such as copper, nickel, cobalt, chromium, zinc and lead are essential for bacterial growth in very small quantities but, at higher quantities, are toxic and will prevent the use of the digestate as a fertiliser. Detergents (soap), antibiotics and organic solvents inhibit bacteria. Recovery following toxic inhibition can only be achieved by stopping and flushing or diluting contents to push below the toxic level.

2.2.2.4.8. Mixing/agitation

Some form of mixing or agitation is required to maintain fluid homogeneity, thereby producing process stability. The objectives of mixing are to combine incoming material with bacteria, stop scum formation and avoid pronounced temperature gradients within the digester. Rapid mixing can disrupt bacterial communities whereas mixing too slow can cause short-circuiting.

2.2.2.4.9. Pathogens

Certain pathogenic bacteria and viruses in MSW can pose a risk of infection to workers. At-risk material needs pre-treatment at 70°C for at least 1 h.

2.2.2.5. Key Substrate Parameters for Anaerobic Digestion

For efficient biogas production, a clear understanding of the nature of the input substrate has to be made because the properties of the substrate have a direct bearing on the resultant volume of the biodigester, the quantity/quality of output biogas and hence the project cost. Among the substrate parameters that should be ascertained are: Total Solids (TS), Total Volatile Solids (TVS), Substrate Dryness and organic loading rate. These have been summarised as below;

2.2.2.5.1. Total Solids (TS)

This is the total amount of solid matter present in a given substrate. The Total solids' content of a substrate is obtained by weighting the residue or dry material left after drying it for 48 hours at 105°C. The mass obtained is the raw estimation of both the organic and inorganic content of the substrate (N. Curry and P. Pillay, 2012).

2.2.2.5.2. Total Volatile Solids (TVS)

Volatile solids (VS) also referred to as the organic fraction of the total solids represent the digestible portion of the total solids normally expressed as a percentage. It is determined by heating the TS to 550°C for 24 hours. The balance of the process is the inorganic fraction of the TS (H. A. Igoni, 2008).

2.2.2.5.3. Organic Loading Rate (OLR)

Organic loading rate (OLR) represents the amount of organic material that is added to the biodigester within a given amount of time usually expressed volume per day. The OLR gives an indication on the amount of volatile solids to be fed into the digester each day thereby becoming a key parameter in the sizing of the plant (R. Mattocks, 1984).

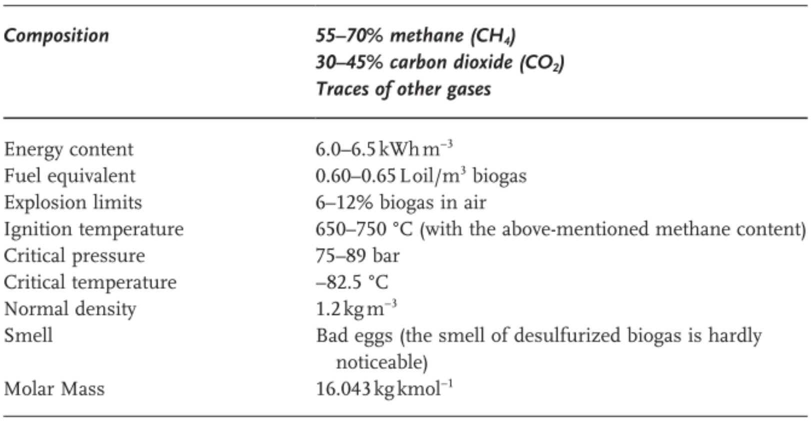
2.2.2.6. Products of Anaerobic Digestion

At the time of the transformation of the organic matter, anaerobic digestion produces biogas and the digestate the residual part of the process. If biogas has an important function like energy source, the digestate, as for him, can be used like amendment of the grounds under certain conditions.

2.2.2.6.1. Biogas

The composition of biogas varies according to the digested matters and the processing time. Usually, the methane concentration ranges between 50 and 80%, 60% being the value most frequently reported by the factories. Besides methane, the other formed principal gas is CO_2. The present gases in weak concentrations are H2S, NH3 besides the steam up to its point of saturation. These last gases must be treated according to use the planned for biogas in order to not damage the equipment. The table below gives the average composition of the biogases obtained by anaerobic digestion.

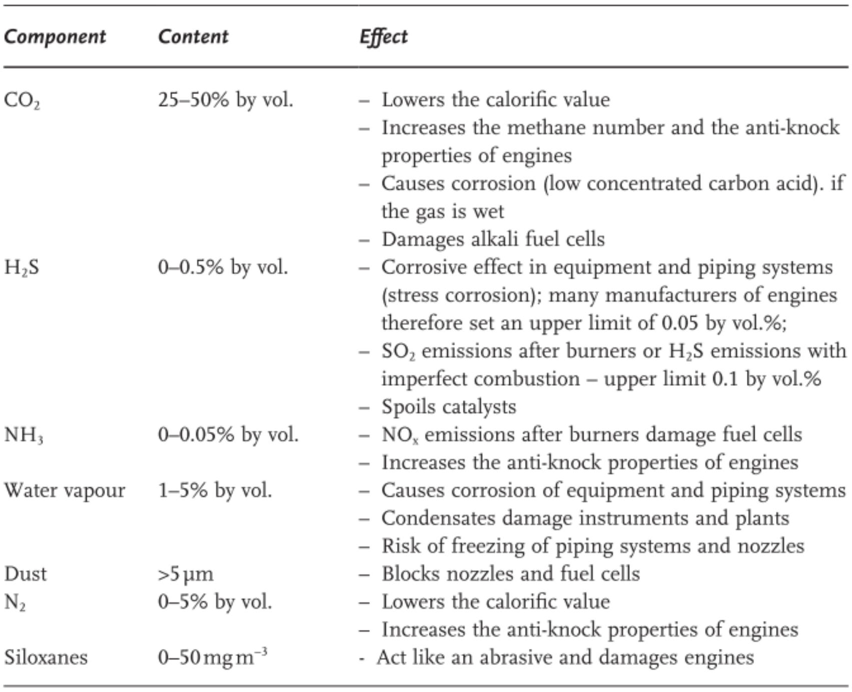
Table 2.2.3: General features of biogas



Composition	***55–70% methane (CH_4)*** ***30–45% carbon dioxide (CO_2)*** ***Traces of other gases***
Energy content	6.0–6.5 kWh m^{-3}
Fuel equivalent	0.60–0.65 Loil/m^3 biogas
Explosion limits	6–12% biogas in air
Ignition temperature	650–750 °C (with the above-mentioned methane content)
Critical pressure	75–89 bar
Critical temperature	–82.5 °C
Normal density	1.2 kg m^{-3}
Smell	Bad eggs (the smell of desulfurized biogas is hardly noticeable)
Molar Mass	16.043 kg $kmol^{-1}$

Source: (Abbasi and Al., 2012)

Table 2.2.4: Typical components and impurities in biogas



Component	***Content***	***Effect***
CO_2	25–50% by vol.	– Lowers the calorific value – Increases the methane number and the anti-knock properties of engines – Causes corrosion (low concentrated carbon acid). if the gas is wet – Damages alkali fuel cells
H_2S	0–0.5% by vol.	– Corrosive effect in equipment and piping systems (stress corrosion); many manufacturers of engines therefore set an upper limit of 0.05 by vol.%; – SO_2 emissions after burners or H_2S emissions with imperfect combustion – upper limit 0.1 by vol.% – Spoils catalysts
NH_3	0–0.05% by vol.	– NO_x emissions after burners damage fuel cells – Increases the anti-knock properties of engines
Water vapour	1–5% by vol.	– Causes corrosion of equipment and piping systems – Condensates damage instruments and plants – Risk of freezing of piping systems and nozzles
Dust	>5 µm	– Blocks nozzles and fuel cells
N_2	0–5% by vol.	– Lowers the calorific value – Increases the anti-knock properties of engines
Siloxanes	0–50 mg m^{-3}	- Act like an abrasive and damages engines

Source: (Abbasi and Al., 2012)

2.2.2.6.2. Digestate and eluat

The digestate is a residue similar to the humus, partially stable and rich in organic components. In the case of the use of the organic solid inputs for biogas production, it has, on the outlet side of the digester, a pasty consistency and often emits unpleasant odours. The excess of liquid can be extracted for feeding back the system out of water and specialized micro-organisms and/or to minimize the quantities of matters to being transported. In several cases, the solid fraction of the digestate is then perforated and the result used as amendment of the soils. The liquid part, **eluat**, can be used directly as liquid fertilizer because of its wealth of nutritive elements.

2.2.2.7. Advantages of biogas production

Anaerobic digestion offers multiple advantages among which one can quote:

- **The reduction of the odours:** the matter dries biodegradable, person in charge of the odours is destroyed in first by digestion;
- **Reduction in the volume of muds, waste, the industrial effluents or the animal manure:** it is given by the rate of abatement of the dry matters. One notes also a strong reduction in the rate of the volatile matters;
- **Production of methane:** principal component of biogas, its content is expressed in m^3 per ton of volatile matters degraded;
- **Attenuation of the health risks:** biogas production through AD leads to the destruction of most of the pathogenic germs, the reduction of the risks of toxicity of the elements traces and the reduction of the contents of organic contaminants. Indeed, organic many micro pollutants are then transformed into biogas or toxic components.

2.2.2.8. Anaerobic digestion technologies for biowaste

The choice of the basic AD design is influenced by the technical suitability, cost-effectiveness, and the availability of local skills and materials. In developing countries, the design selection is largely determined by the prevailing and proven design in the region, which in turn depends on the climatic, economic and substrate specific conditions (Lohri, 2012).

The three main types of digesters that have been implemented in developing countries are the fixed-dome digester, the floating-drum digester and the tubular digester, all of which are wet digestion systems operated in continuous mode under mesophilic conditions. These three types are inexpensive, built with locally available material, easy to handle, do not have many moving parts and are thus less prone to failure. A further digester type, the garage-type digester, which is operated as a dry digestion system in batch-mode, is considered as another potential biogas technology suitable for developing countries. Although this technology is being tested in Ghana by converting a used shipping container, it is not yet ready for the commercial market as no viable low –cost design exists that has been successfully tested at full-scale.

2.2.2.8.1. Fixed-dome digester

As with the floating dome, this reactor consists of two major parts, the digester and the gas holder. Based on the Chinese drumless model shown in Figure , the difference is that the dome is fixed in place and cannot move. Fixed-dome reactors are cheaper on a volumetric throughput basis compared with floating-dome reactors. Gas accumulation exerts pressure on the slurry, displacing it to inlet and outlet tanks. Digested slurry that is more than 50 days old is lighter than fresh slurry so that it forms a layer between the gas and the fresh slurry, which is displaced by the pressure, forcing it out of the digester. The feed slurry in fixed-dome reactors typically have solids contents of between 4% and 8%. The most common reactor size and HRT is 2 m3 and 50 to 66 days, respectively (Abbasi et al., 2012). Digesters are limited to less than 20 m3 due to the pressure build up from biogas, and the risk of cracks forming if pressures are exceeded.

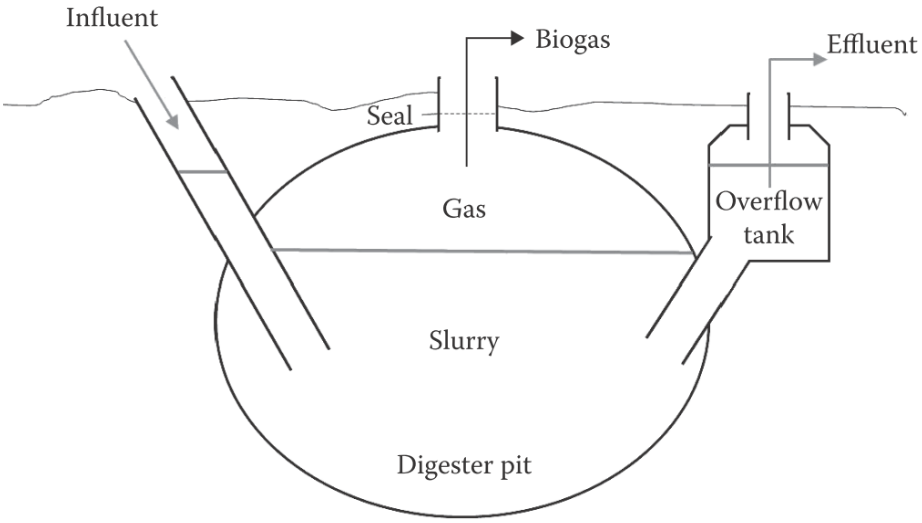


Figure 2.5: Fixed-Dome digester

Table 2.2.5: Advantages and disadvantages of fixed-dome digesters (Kossmann et al)

Advantages	**Disadvantages**
• Relative low construction costs • Long life span if well-constructed • Absence of moving parts or corroding metal parts • Underground construction saves space and protects the digester from temperature fluctuations • Local construction provides opportunities for skilled local employment	• Certain specific technical skills are required to ensure a gas-tight construction • Fluctuating gas pressure depending on volume of stored gas • Special sealant is required for the inside plastering of the gasholder (e.g. bee wax – engine oil mixture, acrylic emulsion) • Gas leaks may occur when not constructed by experienced masons • Difficult to construct in bedrock • Difficult to repair once constructed as the reactor is located under soil

2.2.2.8.2. Floating-drum digester

The floating dome reactor, as shown in Figure 7.3, consists of two major parts, the digester and the gas holder. As biogas is produced, it exerts upward pressure on the gas holder, causing it to rise. There is no need for any safety valve as the dome is free to rise under pressure; therefore, there is never extensive pressure buildup. If the digester is greater than 1.5 m in diameter, a vertical partition wall is installed in the middle to prevent short-circuiting and encourage complete digestion. Capacities typically range from 1 to 8 m3, but may be as large as 100 m3, processing a slurry with total solids content of approximately 9%, with an HRT of 40 to 55 days (Abbasi et al. 2012).

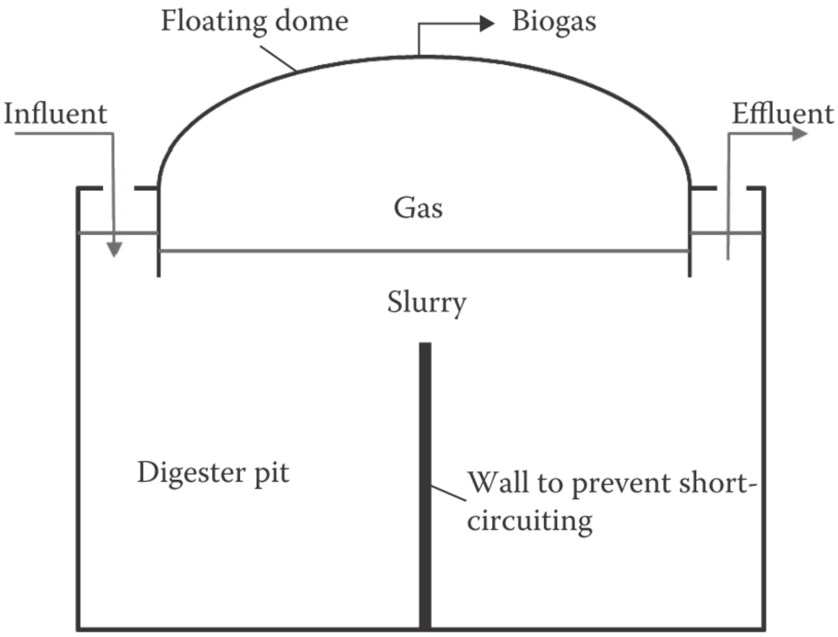


Figure 2.6: Floating-Drum digester

Table 2.2.6: Advantages and disadvantages of floating-drum digesters (Kossmann et al)

Advantages	Disadvantages
• Simple and easy operation • The volume of stored gas is directly visible • Constant gas pressure • Relatively easy construction • Construction errors do not lead to major • problems in operation and gas yield	• High material costs for steel drum • Susceptibility of steel parts to corrosion (because of this, floating-drum plants have a shorter life span than fixed-dome plants) • Regular maintenance costs for the painting of the drum (if made of steel) • If fibrous substrates are used, the gasholder shows a tendency to get “stuck” in the scum layer (if gasholder floats on slurry)

2.2.2.8.3. Tubular digester or Balloon digester

A tubular biogas plant consists of a longitudinal shaped heat-sealed, weather resistant plastic or rubber bag (balloon) that serves as digester and gas holder in one. The gas is stored in the upper part of the balloon. The inlet and outlet are attached directly to the skin of the balloon. As a result of the longitudinal shape, no short-circuiting occurs, but since tubular digesters typically have no stirring device, active mixing is limited and digestate flows through the reactor in a plug-flow manner. Gas pressure can be increased by placing weights on the balloon while taking care not to damage it. Figure 8 shows a schematic representation of a typical tubular digester.

The benefit of these digesters is that they can be constructed at low cost by standardised prefabrication. Additionally, the shallow below ground installation makes them suitable for use in areas with a high groundwater table. However, the plastic balloon is quite fragile and susceptible to mechanical damage and has a relatively short life span of 2 – 5 years (Nzila et al., 2012).

To avoid damage to and deterioration of the balloon, it is also important to protect the bag from direct solar radiation with a roof. Additionally wire-mesh fence protects against damage by animals. Table 9 highlights the advantages and disadvantages of this design type.

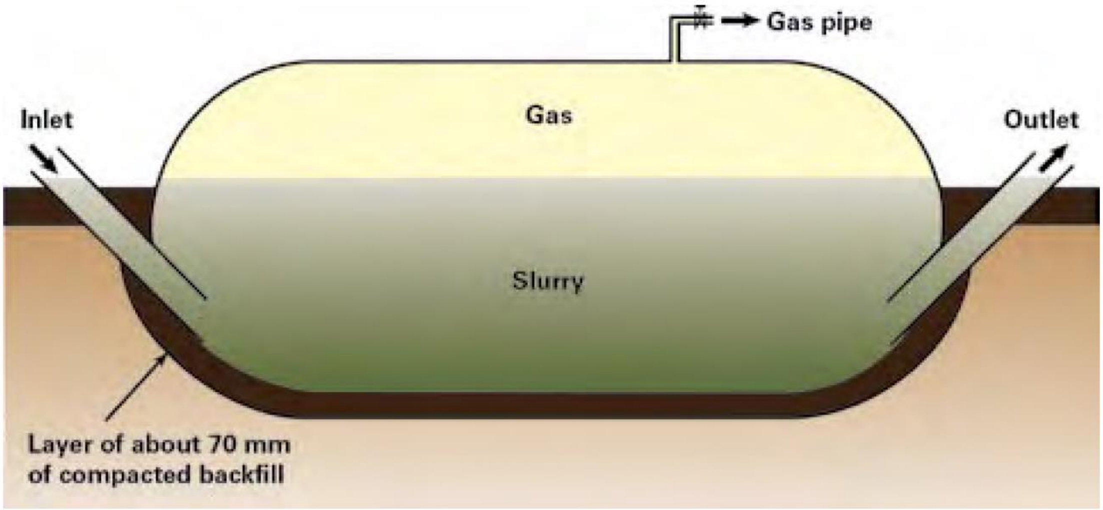


Figure 2.7: Balloon digester

Table 2.2.7: Advantages and disadvantages of floating-drum digesters (Kossmann et al)

Advantages	Disadvantages
• Low construction cost • Ease of transportation • Easy to construct • High digester temperatures in warm climates • Uncomplicated emptying and maintenance	• Relative short lifespan • Susceptibility to mechanical damage • Material usually not available locally • Low gas pressure requires extra weights • Scum cannot be removed from digester • Local craftsmen are rarely in a position to repair a damaged balloon

• Shallow installation depth suitable for use in areas with a high groundwater table or hard bedrock	

CHAPTER 3: MATERIALS AND METHODS

3.1. PRESENTATION OF YOPOUGON

3.1.1. Institutional statute

It is owing to the law N° 78-07 of the bearing January 9th, 1978 creation of the communes of full with exercise in Ivory Coast that Yopougon becomes in 1980 a territorial collectivity, an administrative entity equipped with the legal entity and financial autonomy. Decentralized territorial collectivity, the commune of Yopougon is part of the 13 communes of the district of Abidjan.

In its development policy, in view of competences which are reserved for it by the law, the commune of Yopougon in its sectorial plans, operations and actions, must be in harmony with those of the district which in their turn must tally with the national policy adopted in each sector.

3.1.2. Geography

Yopougon is located in the world map at the latitude **5°18’34 North** and longitude **-4°0’45 West** and it extends on a surface from **153.06 km2** according to its town hall making from the vastest commune from the town of Abidjan but not for Abidjan District. Thus, Yopougon is the commune most populated not only of Abidjan but also of the Ivory Coast. It is located all west of the town of Abidjan, is bounded in north by the commune of Abobo and the town of Anyama; in the south by the Atlantic Ocean; in the east by Attécoubé and the west by Songon.

The communal territory of Yopougon is composed of 14 districts namely: Selmer, New District, Red Roofs, Sideci, Sogefiha, Wassakara, Gesco, Port-Bouët 2, industrial Park, Niangon Southern, Military camp, Morocco.

The common one also counts eleven (11) villages of the ethnos groups Atchan and Akyé. They are Adiapodoumé, Andokoi, Azito, Niangon Adjamé, Niangon Attié, Niangon Lokoa, P.K.17, Yopougon Kouté, Yopougon Santé, Yopougon Attié, Béago and the group Boulay island.

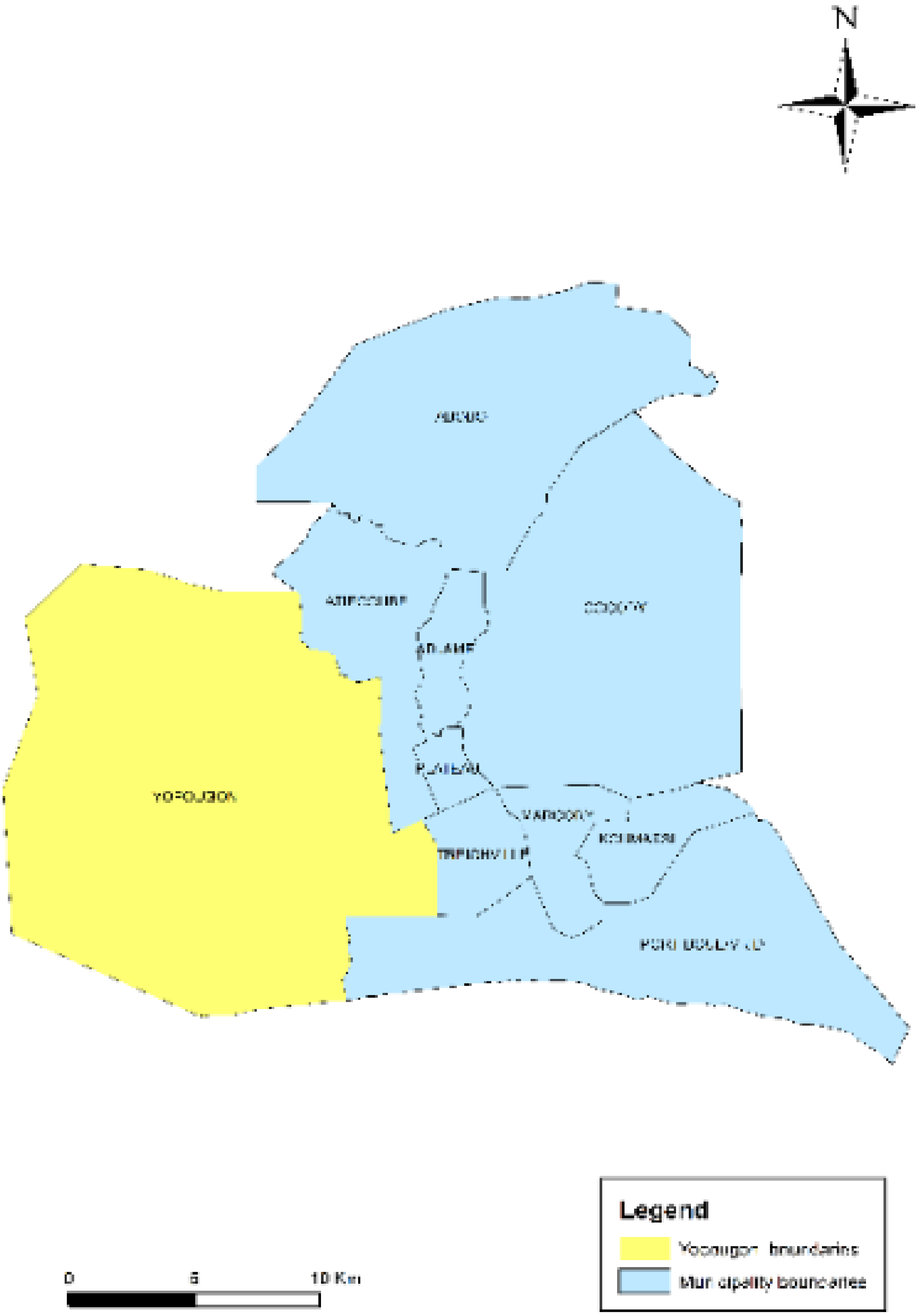


Figure 3.5: Map of Abidjan including the location of Yopougon

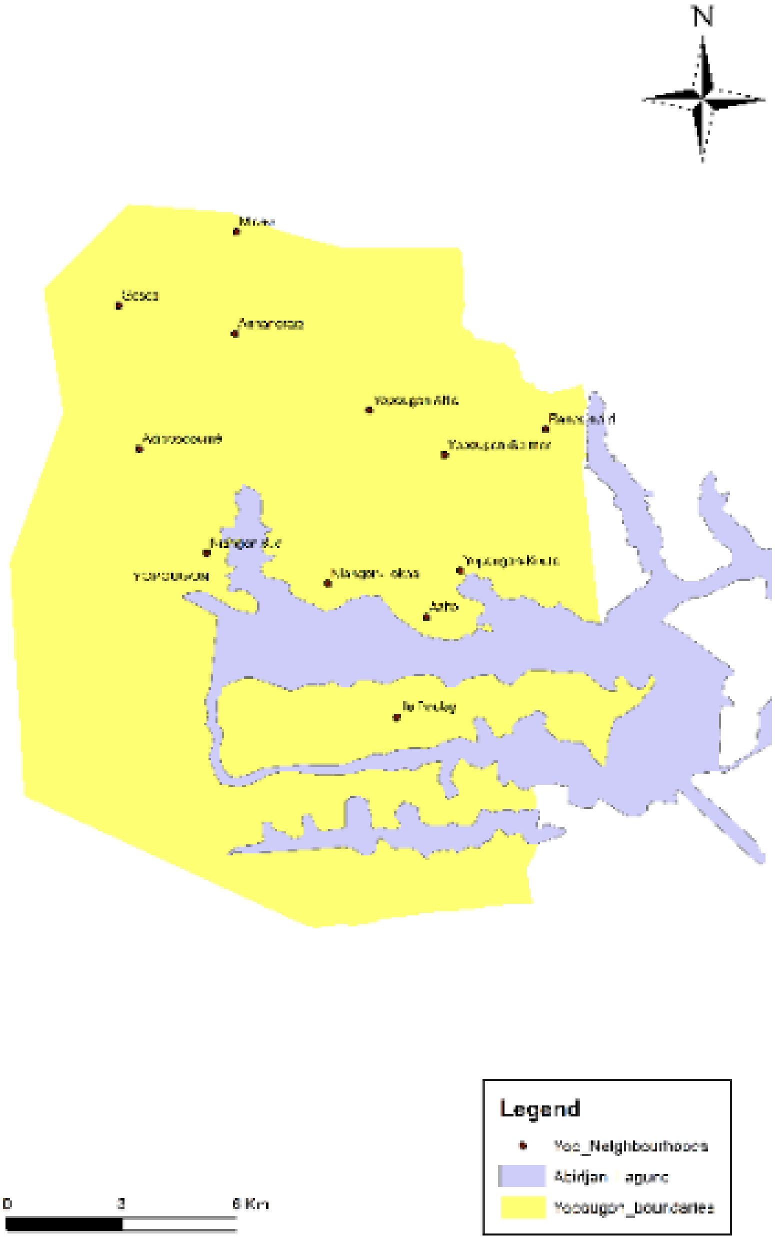


Figure 3.6: Map of Yopougon municipality

3.1.3. Population

The general and real information of the population of the commune of Yopougon arises from the census carried out in 2014 on all the territory of the Ivory Coast. The population according to the forecasts of the RGPH of the commune of Yopougon is estimated at approximately 1 100 000 inhabitants, information supported by the engineering service of the municipality. Information of the population of Yopougon which was established according to the census of 2014 us indicates a population of 1 071 543 inhabitants with 219 651 households with averagely about 5 people per household and including 523 952 men and 547 591 women thus a density of 7000.8 inhabitants/km2 with a peri-urban population estimated at 34% of the total population (RGPH, 2014). The residences alternate between buildings of apartments and low houses of average standing.

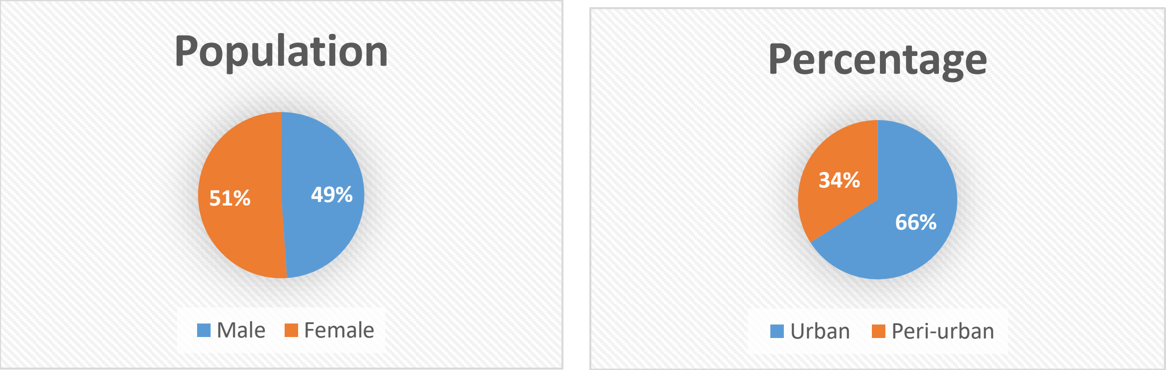


Figure 3.7: Share of population according to the gender and urbanisation level (i.e RGPH 2014)

This population has known a real evolution throughout the time, it has been based on a growth of 3.16 % (BURGEAP, 2011). The table and figure below describes the evolution of the population from 1975 to 2020 (forecast):

Table 3.1.1: Population evolution of Yopougon from 1975 to 2020 (Source: BURGEAP, 2010):

Years	**1975**	**1988**	**1998**	**2002**	**2005**	**2010**	**2015**	**2020**
Population	78 700	374 524	688 235	744 016	813 006	942 497	1 092 613	1 266 637

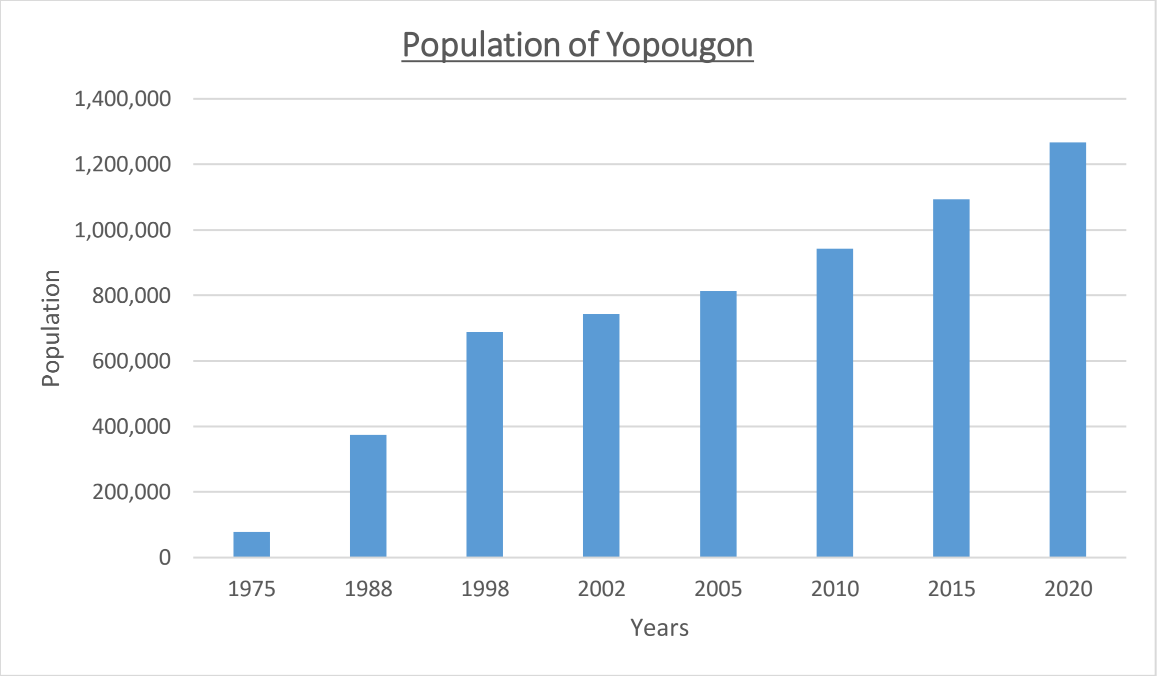


Figure 3.8: Population's evolution of Yopougon (i.e. BURGEAP)

3.1.4. Vegetation

The commune of Yopougon is characterized by the existence of forests, in particular the classified forest of Banco, ecological site of international repute which borders the commune and has 3750 hectares of protected areas. There is also the classified forest of Anguédédou located near the park of Banco and not far from and the Correction prison of Abidjan (MACA).

If these two forests surround Yopougon, the commune itself seems an urban development reach primarily made up of constructions in cement breeze block in an environment without large vegetation.

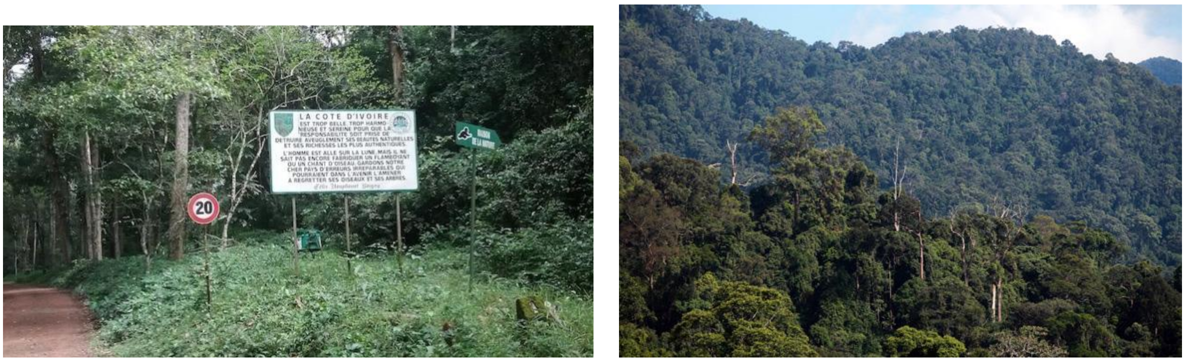


Figure 3.9: Forest of Banco

3.1.5. Climate

Yopougon being a commune of the coastal area of the country is a fairly wet climate marked by three seasons lasting the year with knowing the rain season which generally extends in Mars until July and from September to November, a fairly dry season with a strong followed sunning by hot and wet wind marking a weak rainfall and finally a dry season marked by the harmattan, a hot and dry wind recorded during the months of December and January. The tables and graphs below will give us a summary description of the climate of the zone of Yopougon:

Table 3.1.2: Average temperature and rainfall of Yopougon (Source: Climatedata.org)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual avg**
Avg of temperature (°C)	26.7	27.6	27.7	27.7	27.2	25.8	25.2	24.2	25.2	26.1	26.9	26.9	26.4
Rainfall (mm)	22	70	95	139	264	543	148	45	86	151	136	64	1763

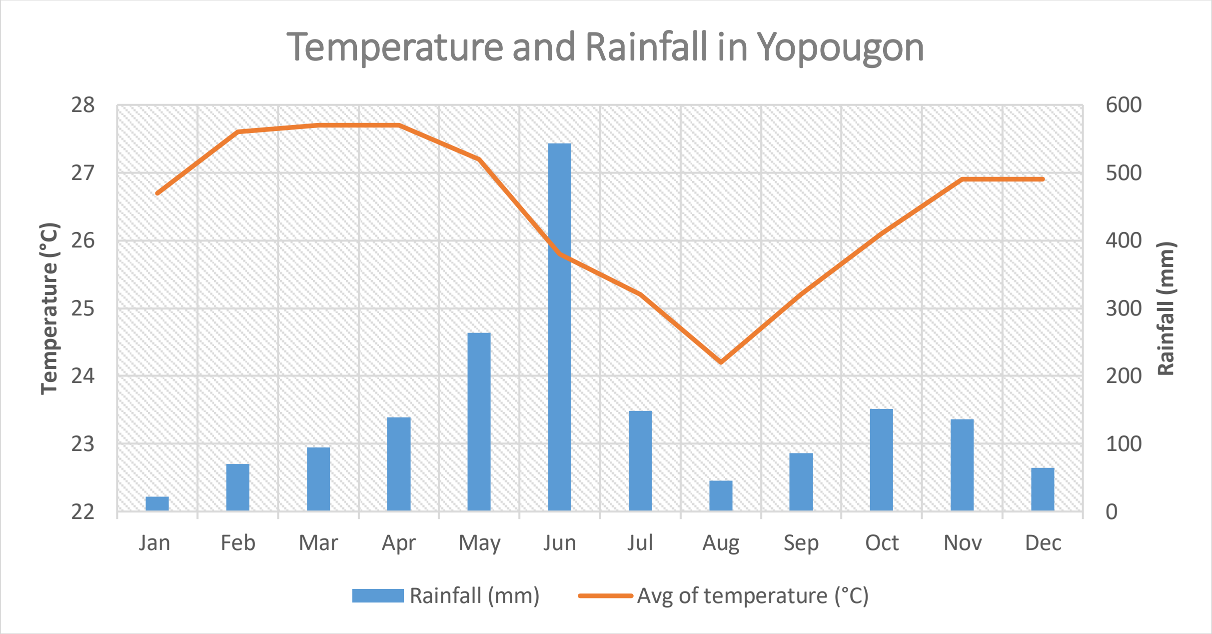


Figure 3.10: Rainfall and temperature in Yopougon

This graph shows that the annual rainfall in Yopougon is 1763 mm with an annual average temperature of 26.4°C. le wettest month over the year is June witth a rainfall of 543 mm and driest is January with 22 mm and finally the hottest month are March and April with an average temperature of 27.7°C and the coolest is August with 24.2°C.

3.1.6. Economy

3.1.6.1. Industry

The commune is an important centre of economic activities because it has the greatest industrial park of the town of Abidjan. It is the largest economic commune of zone UEMOA with 300 industrial companies.

Most emblematic of local industries are New Perfumery Gandour, NESTLE, CIMAF, Eurolait, Satoci, Cargill Cocoa (a unit specialized in the cocoa crushing has a capacity of transformation of 120 thousand tons broad beans which produces powder, butter and mass of cocoa). The Steel-works of Ivory Coast of the Eurofind group which reached the turnover 21.6 billion in 2012.

3.1.6.2. Banks

Several international and national large banks share financial space with knowing the SGBCI, Ecobank, the BIAO, the BICICI, BNI, BHCI but also of the companies of financing of microphone-projects which are used as banks for the small operators in particular the COOPEC, the CREP-COOPERAGRI and the CECP which has more half of the customers of banks in Ivory Coast.

3.1.6.3. Trade and services

The trade and the services account for 82% of local employment. They are houses of distribution of construction equipment, manufactured goods, clothing, they are also agencies of distribution of the marketing companies and industrial of the city. The commune also has hotels, of stations of petrol, distribution networks of food products and food not counting the 40 markets of proximities which gather approximately 25 000 tradesmen and salesmen. There is also through the principal and secondary arteries of the refreshment bars, of the hairdressing salons, the restaurants and the distributers of computer materials.

3.1.6.4. Transport

Transport provides 13 870 employments. There are the communal taxis which transport the users of the commune of one district to the other, the minibuses, and the taxis meters or inter-commune which serve the neighbouring districts.

The national company of public transport, SOTRA, also transports the users of common the worms of other communes of the District.

3.1.7. Typology of habitats in Yopougon

The Master Plan of Abidjan (1996) defines eight types of habitat that are categorized into four major groups (Table precarious housing, common compound housing, individual housing of all types, and collective housing of all types combined. So that characterization of habitat is also applied for Yopougon municipality.

Table 3.1.3: Different types of habitat in Yopougon

Habitat groups	**Habitat types**	**Characteristics**
Spontaneous habitat	Precarious habitat	It is defined as a set of houses built without title
Evolutionary habitat	Common compound habitat	It is a set of buildings built around a common compound. Appears mostly at the village type.
	Economic collective habitat	It also corresponds to the evolutionary habitat. They are constructions in strips on reduced spaces, realized most often by real estate companies
Economic habitat	Medium standing collective habitat	They are constructions in bands or in height carried out by the State or by private individuals.
	collective habitat Good standing	It also corresponds to the economic habitat. These are residences of good standing.
	Economic individual habitat	It is the set of individual homes of economic standing built by the State or by individuals. This habitat also corresponds to the economic habitat.
	Individual habitat medium standing	They are individual constructions on small and medium plots of average standing.
Residential habitat	Individual habitat high standing	These are individual homes on large plots of high standing. This habitat is accessible only to the most affluent social class.

As part of a study carried out on the characterization of urban waste in the District of Abidjan, TERRABO (2010) selected four types of habitats (Table IV) in carrying out this study based on Thierry's definitions. Paulais (1988) and those of the Master Plan of Abidjan (1996).

Table 3.1.4:Correspondence of standings

Standings	**Correspondence (Abidjan Master Plan)**
High Standards	Residential habitat
Medium standing	Economic habitat
Low standing	Evolutionary habitat
Rural habitat	Spontaneous habitat

Source: (TERRABO-Ingenieur CONSEIL, 2010)

For our study, it is judicious to focus on an area that is more vulnerable face to that poor waste management. By the way, the survey has been oriented to a semi-rural area in Yopougon called BEAGO which is a part of the district of Koute.

3.2. FOCUS STUDY AREA

As said previously, the focus area is BEAGO a semi-rural place located in Yopougon where people have a rural lifestyle because of its political organization. The picture below:

Figure 3.11: Location of the focus study area

As shown by the picture above, the area is bordered by the Ebrie lagoon which offers to the population a good access to fishing practice that has been considered as the main activity over there.

The area will follow the same data stream with Yopougon in terms of climate data and about the social condition, people have mostly low income and live in evolutionary habitat described by common compound habitat that are grouped in the same area where we will focus on only one after the 2 weeks' survey for the feasibility study for biogas production in BEAGO and for further studies expand to all communities over the township. The picture below shows the targeted group of households:

Figure 3.12: the selected community (group of households)

In the picture, the targeted group of households is the part surrounded in yellow. The part gathers totally **22 households** with **136 inhabitants**. Therefore, the 2 weeks' survey gives the necessary data about that place for biogas production from the waste produced in those households.

3.3. METHODS

This part of our study describes in detail the different stages of the feasibility study of biogas production in households of BEAGO located in Yopougon commune. It will consist of showing the technical feasibility that emerges from the design of mini-reactor to produce biogas for the households from their own trash. Then this part will deal with the environmental analysis of producing biogas in households through prose based on data collected during the survey carried out by the company ***SEP Ingénierie*** with the households in their project of prospects of recovery of domestic waste within the commune. Finally, we will show the benefits gained in terms of safeguarding the environment.

3.3.1. Technical feasibility

3.3.1.1. Model

The model will be based on the biowaste produced in the households of the surrounded area on the map above. Biowaste is mainly the separated kitchen and garden waste from private households. There are differences between biowaste quantities produced within a municipality and the quantities assumed to be collected, due to the fact that the quantities of biowaste are depending on the participation rate of citizens and the capture rate. Some of the organic waste is not suitable for anaerobic digestion, such as wood and other lignin containing waste materials. The biowaste composition varies depending on the geographic area and the income level. Generally speaking, it can contain vegetables, fruits, gardening residues, organic materials from animals or the entire kitchen waste and garden waste.

The idea is to take into consideration the standard data about the daily waste production per capita in Abidjan and by the way for a semi-rural community like BEAGO the standard is **0.8 kg/day/capita** according to the last data received by the department of sanitation at BNETD (BNETD, 2018). The suit of the study will be based on the data collected during the 2 weeks’ survey with the team of **SEP Ingenierie** towards the different families of that targeted community. The survey has been consisting of data gathering about the waste composition and the energy demand in the area wherefrom, the biowaste availability could be simulate for the 2 weeks and then the biogas production regarding the amount of feedstock obtained per day. The composition of the trash analyzed has been done through weighting the sorted waste.

3.3.1.2. Analysis and Calculation

2.1.1.1. Biogas analysis

The data gathered from the survey will help us to the amount of waste produced in the community according to the type. The analysis will consist of determining the biogas production for data collected each day of the survey and at the end consider the mean to size the digester able to contain the amount of waste for biogas production. Moreover, based on the daily waste production per capita which is 0.8 kg/day/inhabitant and the population registered in the community which is 136 inhabitants the total amount of waste produced is **108.8 kg per day** for the entire community wherefrom, it will be obtained the amount of biowaste according to the daily data collected.

The total amount of biogas that can be produced will be calculated through combination of the total food amount, VS percentage and the methane yield. Such as;

$$\boldsymbol{Daily\ Biogas\ Production = OLR \times Biogas\ Yield \times Active\ volume\ of\ digester}$$

(Equation 3.1)

Where;

OLR is the Over Loading Rate in kg VS / m^3 reactor volume such as: $OLR = \frac{Q \times S}{V}$

S is the concentration of the substrate in the inflow in kg VS / m^3

Q is the substrate flow rate in m^3/day.

The biogas yield is mainly based on experimental values according to the feedstock used and in our case it is about mixture of fruit/vegetable/food waste.

2.1.1.2. Active volume of the digester

The active volume of the digester is determined by the following equation:

$$\boldsymbol{V = Q \times HRT} \qquad \text{(Equation 3.2)}$$

Where;

Q is the volumetric flow of the slurry in m^3/day

HRT is the Hydraulic Retention Time in days

2.1.1.3. Volume of the gas holder

The size of the gas holder depends on the gas production and the consumption. The gas production capacity depends on the gas yield of a given substrate. The gasholder capacity, Vg was computed using Equation below:

$$\boldsymbol{Vg = 0.6 \times G} \qquad \text{(Equation 3.3)}$$

Where;

Vg is the gas holder volume in m^3

G is the daily biogas production in m^3

2.1.1.4. Volume of the digester

The total volume of the digester is computed from the sum of that of the gas holder and the active volume through the equation:

$$\boldsymbol{V_D = V + Vg} \qquad \text{(Equation 3.4)}$$

Where;

V_D is the volume of the digester in m^3

V is the active volume

Vg is the volume of the gas holder

2.1.1.5. Dimensions of the digester

KVIC (2009) recommends a height or depth to diameter ratio of between 1.0 and 1.3 is suitable for all digesters. The height of the digester is determined using the equation below:

$$\boldsymbol{V_D = \frac{\pi d^2 h}{4}} \qquad \text{(Equation 3.5)}$$

Where

V_D is the total volume of the digester in m^3

d is the diameter of the digester in m

h is the depth of the digester in m

3.3.2. Environmental analysis

The methane being a major part (60%) of the biogas produced has been considered as being very harmful gas for the environment about 21 times more greenhouse effect than that of the CO2 which is also a major part (~35%) and a greenhouse gas. It will accordingly define the amount of greenhouse gas erased through biogas used instead of leave people dump their waste at the landfill. Beside of this, the fuel used to fulfil the energy demand in the households could help to know how much CO_2 emission will be reduced through biogas production. Therefore, we have to determine the fuel used and the CO_2 emission of each fuel used.

3.3.3. Questionnaire

As already said, the 2 weeks' survey has been consistent to fill a questionnaire concerning the life condition of the population of BEAGO. That questionnaire was about the waste composition, the energy demand and test the interest and awareness of the population about biogas technology. Those questions were as follows:

- Which fuel do you usually use for cooking?
- How much of that or those fuel(s) do you use in average per day?
- How much electricity do you consume per day?
- How do you get electricity for your need?
- Were you aware that your fruit/vegetable/food waste could be used to produced methane (biogas)?
- Would you be interested to the construction of plant for biogas production from those wastes?
- If Yes, would you be willing to separate your fruit/vegetable/food waste for biogas production?
- What would you use the biogas produced for?

Those questions above have to be answered by the population and the remaining part is the waste composition to know the share of the biowaste to be used as feedstock so the part has been on the responsibility of the team sent for the survey through weighting the waste produced usually.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. RESULTS

This part will be about the findings after the data gathered for our study. It will figure out the technology chosen with its different characteristics and the working mode in order for the beneficiaries to get all information around the use of that technology.

4.1.1. Availability of the feedstock

The data on discarded fruit/vegetable/food waste as mentioned in the preceding sections were gathered from the households of the target area in BEAGO. Figure 4.1 shows the dispersion of the waste generated during 2 weeks based on the standard data about the amount of waste generated per capita. It can be clearly seen the considered biowaste occupies the majority of the wastes generated. The value considered in the figure is the percentage of the different components of the trash analyzed.

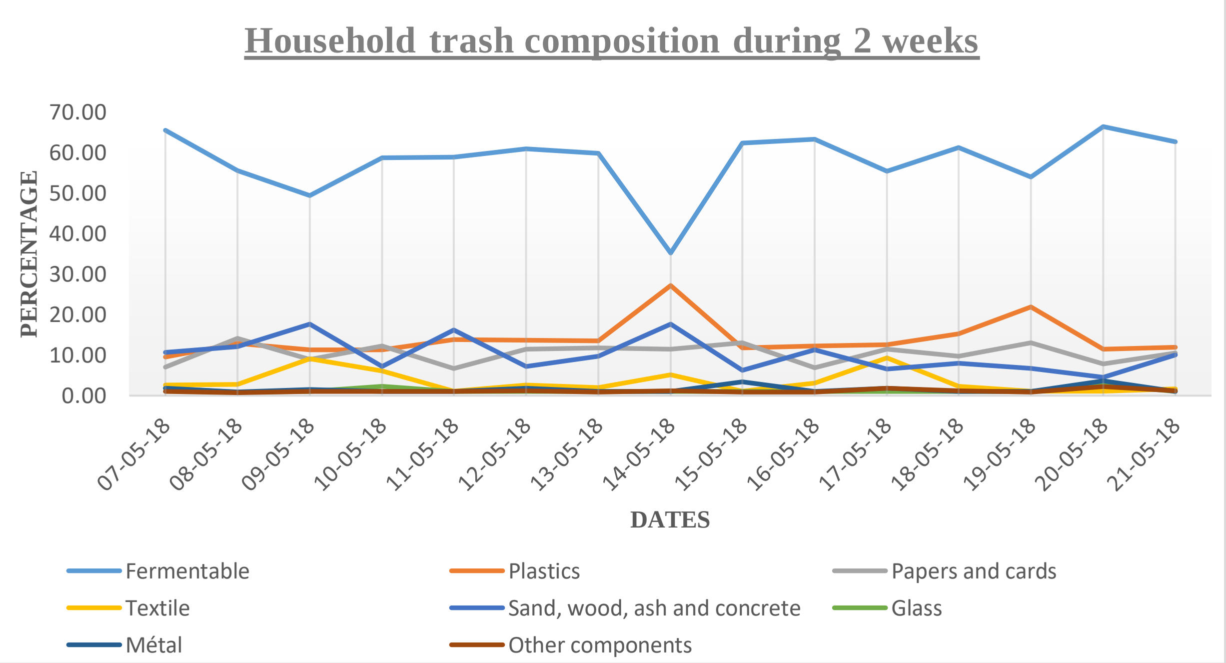


Figure 4.13: Share of the components of trash generated in the targeted area

From the figure above and calculation made, the average value can be as follows in the figure 4.2:

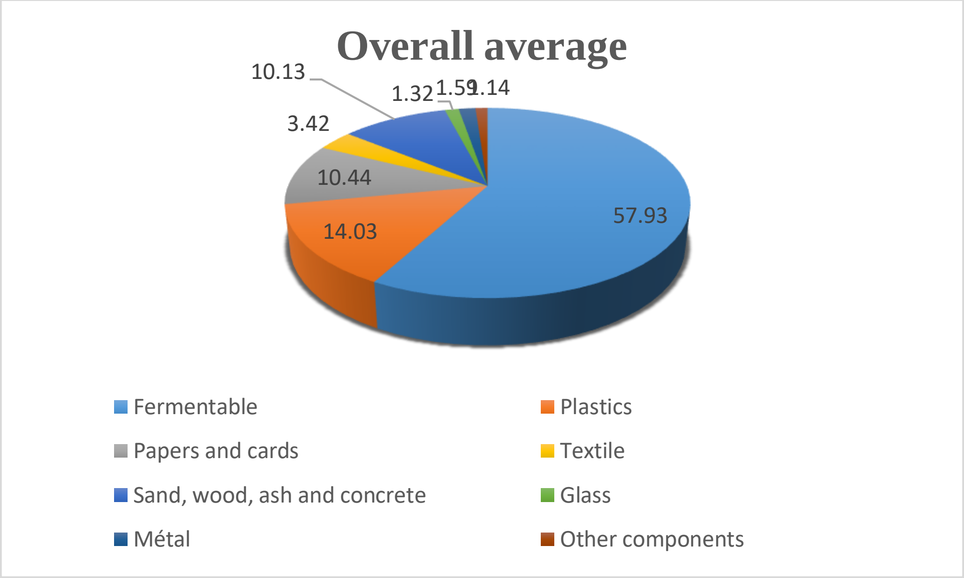


Figure 4.14: The average composition of the household trash

Like the previous figure, the majority share is for the biowaste to be used for biogas production at **57.93%** as average share in the total waste generated for our study area.

4.1.2.Biogas production

The biogas production will be calculated through the different values gathered for each day. It means that each biowaste share will be considered as a case for biogas production computation.

4.1.2.1. Feedstock characteristics

For this part of our study, we will be using the biodegradable fraction of household waste that comply to the different characteristics showed in the table below:

Table 4.1.1: Characteristics of the feedstock

Parameter	Value
Total Solids (TS)	27.14%
Moisture Content (MC)	72.86%
Volatile Solids (VS) (% of TS)	94.90%
Fixed Solids (FS) (% of TS)	5.1%
Density	775.0 kg/m3
C,H,O,N	52.80%, 6.02%, 38.42%, 2.1%

C:N ratio	25:1

Source: (BNETD, 2016)

4.1.2.2. Daily total biowaste available as feedstock for AD

Knowing the characteristics of the waste used, it is possible to calculated the amount of the parameters of the feedstock such as total solids (TS) and volatile solids (VS). This raw feedstock will be diluted with water in a ratio of one-part waste to three parts water. This will result in a slurry which can be easily flushed into the digester. Knowing that the density of the biowaste is **775 kg/m^3**, therefore the volume of the available biowaste can be calculated and taking into the part of water, the substrate flow rate is calculated by the combination of the biowaste and water parts.

In summary, the computation will be based on the following equations:

$$\boldsymbol{Volume\ Feedstock\ (m^3)} = \frac{\boldsymbol{Weight\ biowaste\ (kg)}}{\boldsymbol{Density\left(\frac{kg}{m^3}\right)}} \qquad \text{(Equation 4.1)}$$

$$\boldsymbol{Substrate\ flow\ rate\ (m^3) = Volume\ Feedstock + volume\ water} \qquad \text{(Equation 4.2)}$$

With $volume\ water = 3 \times volume\ feedstock$

$$\boldsymbol{TS\ (kg) = \%TS \times Biowaste\ Weight\ (kg)} \qquad \text{(Equation 4.3)}$$

$$\boldsymbol{VS\ (kg) = \%VS(\%TS) \times TS\ (kg)} \qquad \text{(Equation 4.4)}$$

4.1.2.3. Hydraulic Retention Time (HRT)

The average ambient temperature in Yopougon is 26.4°C and Yopougon being located in Abidjan which is in a tropical area while the ideal HRT for a tropical climate with an average ambient temperature of 25 – 30 °C is recommended to be around **30 days** (Deublein D. and Steinhauser A., 2011), which means that an active reactor volume is obtained from the equation 4.4.

4.1.2.4. Organic Loading Rate (OLR)

It is needed to calculate the concentration of VS in the inflow into the diluted feedstock this is equal to the amount of the concentration S of VS in the inflow. The value of S is the same whatever the case of day chosen that means that we will be based on the average value:

$$S = \frac{16.23}{0.3253} = 49.90\ kg\ VS/m^3 \text{ input}$$

The Organic Loading Rate (OLR) can then be calculated according to the equation as follows:

$$OLR = \frac{Q \times S}{V} \qquad \text{(Equation 4.5)}$$

Whereby Q is the substrate flow rate (m3/day), S is the substrate concentration in the inflow (kg VS /m3) and V is the reactor volume (m^3). OLR being the same for any case, the average will be used so:

Therefore: $OLR = \frac{0.3253 \times 49.90}{9.76} = 1.66$

$$\boldsymbol{OLR = 1.66\ kg\ VS\ per\ m^3\ reactor\ volume\ and\ day}$$

An OLR below 2 kg VS /m3 reactor volume and day is considered ideal for non-stirred AD systems (Chen Y., 2008).

4.1.2.5. Estimation of the daily biogas production

- Theoretical Potential B_0 for biogas production in m^3/kg of VS

The value of B_0 will be assumed according to the experimental value set by Khalid (2011) as showed in the table below:

Table 4.1.2: Methane yield recorded from anaerobic digestion of organic solid waste

Substrate	Methane Yield (L / kg VS)
Palm oil mill waste	610
Municipal solid waste	360 – 530
Fruit and vegetable wastes	420

Food waste	396
Rice straw	350
Household waste	450
Swine manure	337
Maize silage and straw	312
Food waste leachate	294
Lignin-rich organic waste	200

Source: (Khalid A., 2011)

The table shows that the theoretical value of the potential for methane production can be assumed to **400 L CH_4 /kg VS** for the mixed fruit/vegetable/food waste and for a mixed vegetable/vegetable/food waste the share of methane in the biogas is 60% which means that the theoretical potential B_0 of biogas for the feedstock used is **0.670 m^3/kg VS**

From that value we could get the amount of biogas that can be produced daily according to the different cases as shown in the figure below:

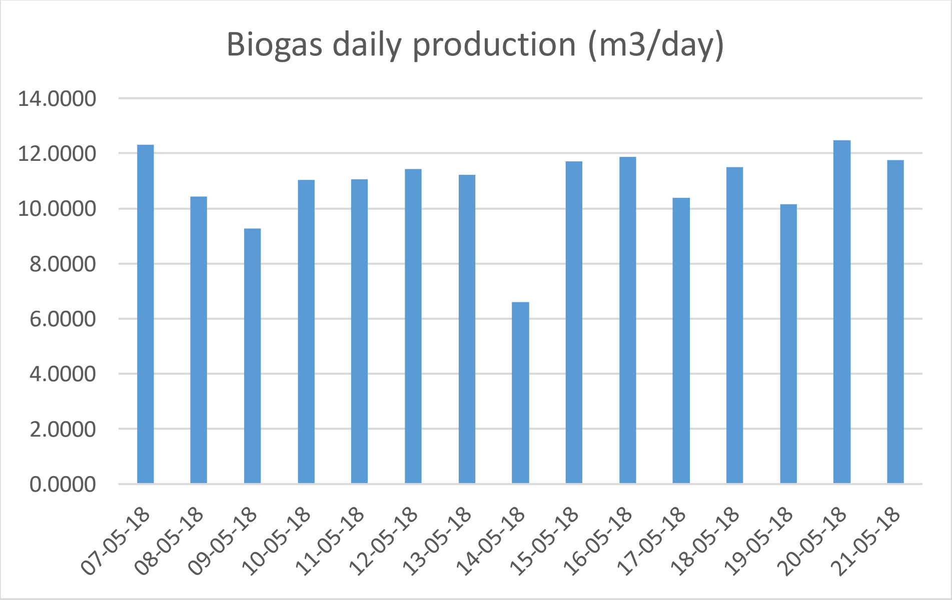


Figure 4.15: The daily production of biogas according to the data collected each day during the survey

For the suit of the study, the average value will be used.

The different values obtained for the average case are in the table below:

Table 4.1.3: Fundamental results for the biogas plant

	Fermentable (%)	**Biowaste for biogas production (kg)**	**Volume of biowaste (m3)**	**Substrate Volume (m3)**	**Active volume (m3)**
General average	57.93	63.03	0.0813	0.3253	9.76

	TS (kg)	**VS (kg)**	**S (kg VS/m3 OM)**	**OLR (kg VS / m3 reactor)**	**Biogas daily production (m3/day)**
General average	17.11	16.23	49.90	1.66	10.88

The tale above shows that the plant will treat **63.03 kg** per day of biowaste which consist of fruit, vegetable and food waste so in the year it is **23 tons** of biowaste that will be used for biogas production. After computation, the amount of biogas produced is estimated to **10.88 m^3 or 3969.91 m^3** in the year.

4.1.3.The AD plant sizing

4.1.3.1. Choice of the technology

Seeing that the amount of biowaste to be used is a bite huge (63.03 kg per day) with a total substrate volume of 0.3253 m^3 per day, the choice will be oriented toward the floating drum plant. This technology is described by a mixing pit, the bio digestion tank and an outlet pit to collect the overflow slurry after the hydraulic retention time. So the sizing will consist of design the inlet the digester and the outlet and for that it will be using the method of KVIC (2007).

4.1.3.2. Size of the Digester

- Active volume or reactor volume and the size of the reactor

This volume has been already obtained from the average values retained for the design such as V = 9.76 m^3. So for the design, 9.8 m^3 will be considered as the volume of the reactor whereas it is slightly above of 9.76 m^3.

The dimensions of the reactor are gotten from the equation 4.3 as established in the table below with a ratio of depth to diameter of 1.1 (h: d = 1.1)

Table 4.1.4: The results for the digester

	Reactor volume V (m3)	**Diameter d (m)**	**Depth h (m)**
Results	9.80	2.25	2.47

In fact, the equation 4.5 has become, $\mathbf{d} = \sqrt[3]{\frac{\mathbf{4 \times V}}{\mathbf{1.1 \times \pi}}}$ seeing that **h = 1.1 d** and was replaced in the equation accordingly.

- Mixing tank

KVIC (2007) recommends that the maximum height of the inlet tank should be **1 m**. The volume of the inlet tank was placed at **50%** more than the daily available volume of feedstock, Q. This capacity of the mixing tank helps to prevent spillage of slurry during mixing thus improving operational convenience to the household. The volume of the mixing tank was computed as follows:

$$\boldsymbol{V_S = 1.5 \times Q} \qquad \text{(Equation 4.6)}$$

Where;

V_S is the volume of the mixing tank in m^3

Q is the substrate inflow rate in m^3/day

The most commonly used shape for mixing tanks is the cylindrical shape. Choosing arbitrarily a depth, h of 0.8 m, the diameter of the mixing tank was computed using the value of V_S and the relation between the volume and the diameter with a known height.

Therefore, we get the results in the table below:

Table 4.1.5: Results for the mixing pit

	Substrate Volume (m3/day)	Volume Vs (m3)	Height h_S (m)	Diameter d_S (m)
Results	0.33	0.50	0.80	0.89

4.1.3.3. The gas holder

This volume taking into consideration the daily production biogas and the multiplication factor that is 0.6 for the gas holder of floating drum plant so for the daily production that is **10.88 m^3 per day**, the gas holder will have a volume V_G of **6.528 m^3** so for the project **6.53 m^3** will be taking as the gas holder volume

KVIC (2007) recommends a diameter of the gasholder of 15 cm less than that of the biogas digester. This allows for movement of the gas holder up and the down without rubbing itself on the biogas digester. Thus the diameter, d_G of the gas holder was computed using the Equation (4.7) while the corresponding height, h_G was determined using Equation (4.8).

$$d_G = d - 0.15 \qquad \text{(Equation 4.7)}$$

$$h_G = \frac{4 \times V_G}{\pi \times d_G^2} \qquad \text{(Equation 4.8)}$$

The results from the equations above are consigned in the table below:

Table 4.1.6: The results for the gas holder

	Biogas daily production (m3/day)	Volume V_G (m3)	Diameter d_G (m)	Height h_G (m)
Results	10.88	6.53	2.10	1.89

Figure 4.4 shows a dimensioned sectional view of the biogas plant while Figure 4.5 shows the plan view of the biogas plant while.

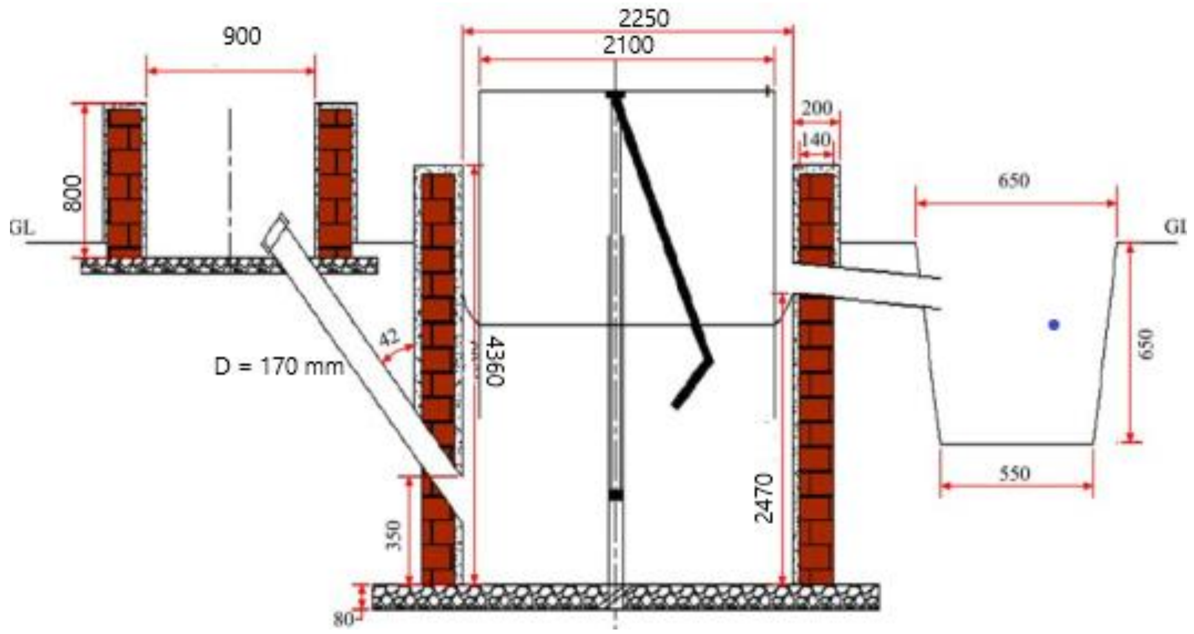


Figure 4.16: Sectional view of the biogas plant

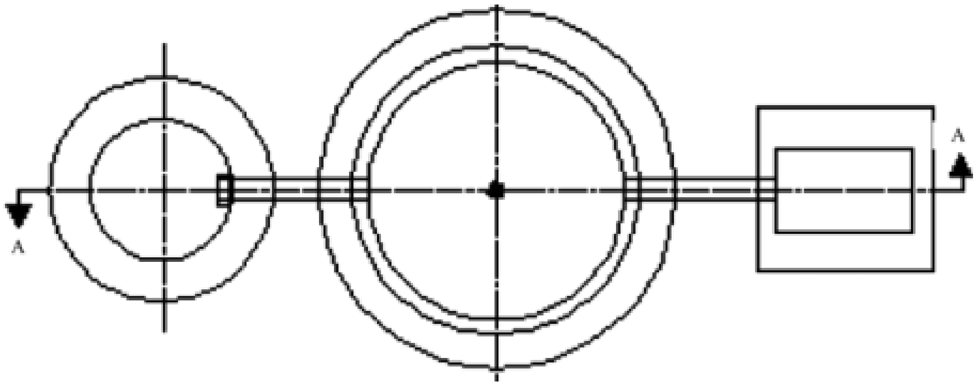


Figure 4.17: Plan view of the biogas plant

4.1.4. Use of the biogas produced

One part of the 2 weeks' survey made in BEAGO mainly in the focus has been to know the interest of people for biogas production. The end of that survey revealed that people are almost entirely interested by biogas for cooking because of the advantage they could gain in term of efficiency and healthy welfare. In fact, the population of BEAGO is still on burden of firewood for cooking and this situation is justified by the low income of the population. However, BEAGO being inside of the Yopougon municipality benefits from national grid for electricity supply so people through biogas see environment safeguard and reduction of disease risks from firewood use. The type of stove used is the three stones stove to burn the wood fuel as shown below in the picture

Figure 4.18: Three stones stove

The end of the project has planned to replace those three stones stove for firewood by biogas stove which looks like the conventional gas stove as shown in the figure below.

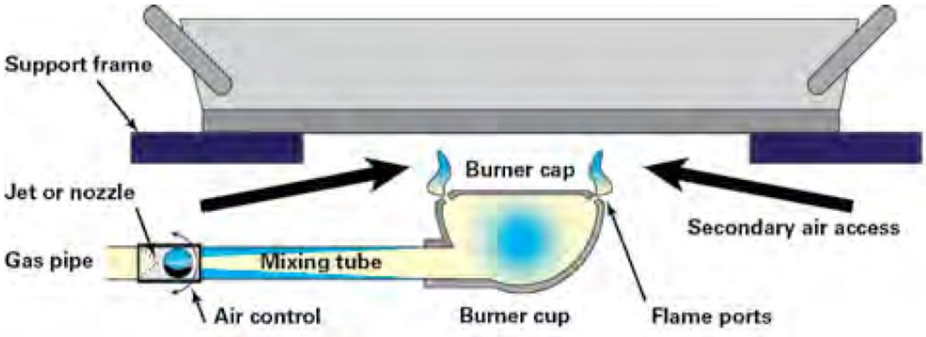


Figure 4.19: Assembly of a typical biogas burner for household cooking

4.1.5. Environmental safeguard

4.1.5.1. Estimating carbon emission saving

The most fuels used currently in the area are firewood and charcoal for cooking. According to the report from the 2 weeks' survey, people in BEAGO use firewood for their daily energy demand for cooking.

The amount of carbon emissions saved depends on the amount of wood fuel replaced by biogas, the net calorific value of wood fuel and the carbon emission factor of wood fuel.

4.1.5.1.1. Determining the energy produced by the biogas plant

The energy produced by the biogas plant depends on the gas produced and the net calorific value, NCV_b of biogas. Since the average net calorific value of biogas is 20 MJ m^{-3} (6 kWh/m^3), the energy produced by the biogas plant was determined using Equation (5.9).

Daily energy production, $Energy = G \times NCV_b$ (Equation 4.9)

The results are consigned in the table below:

Table 4.1.7: Energy produced from biogas

	Biogas daily production (m3/day)	**Energy produced (kWh/day)**	**Energy produced (MWh /Year)**
General average	10.88	65.26	23.82

4.1.5.1.2. Determining the amount of wood replaced by biogas

The amount of wood, Mw replaced by biogas depends on the energy produced by the biogas plant and combustion efficiencies, η_W of biogas stove and wood fuel stove used respectively. The values of the efficiencies are shown in Table 4.8. The amount of wood fuel offset by biogas and total amount of wood, M_Y replaced yearly by targeted area was estimated as shown below.

Since the conventional biogas stove is 55 % efficient, then the useful energy for cooking is equivalent to: 0.55×65.26 = 35.89 kWh/day.

Since the three stone stove is only 8% efficient, it will require more wood to produce the same energy as that generated from biogas as is shown in Equation (4.11).

$$\eta = \frac{Energy\ output}{Energy\ input} \qquad \text{(Equation 4.10)}$$

$$Energy\ input_{wood} = \frac{Energy\ output}{\eta_{Firewood\ stove}} \qquad \text{(Equation 4.11)}$$

Table 4.1.8: Efficiency of stoves using different fuels

Type of stove	**Efficiency (%)**	**Fuel type**

Three stones stove	8.0	Fuel wood, agric-residues
Single and two pot mud stove	13.0	Fuel wood, agric-residues
IDB stove	20.0	Fuel wood
NERD stove	27.0	Fuel wood
Convention biogas stove	55.0	Biogas
Ceylon charcoal stove	30.0	Charcoal

Source: (Perera KKCK, 2002)

The results are consigned in the table below:

Table 4.1.9: Daily values of energy production and saving from biogas

	Biogas daily production (m3/day)	**Energy produced (kWh)**	**Output for biogas stove (kWh/day)**	**Input for firewood (kWh/day)**
General average	10.88	65.26	35.89	448.65

Table 4.1.10: Yearly values of energy production and saving from biogas

	Biogas daily production (m3/year)	**Energy produced (MWh)**	**Output for biogas stove (MWh)**	**Input for Firewood (MWh)**
General average	3969.91	23.82	4.78	163.76

4.1.5.1.3. Determining the carbon emissions saved

The carbon emission savings obtained by implementation of the biogas project depends on the amount of wood fuel offset, net calorific value of wood fuel and the carbon emission factor of wood fuel. The carbon emission savings, ER were therefore computed using Equation (14).

The amount of firewood saved is determined by using the following equation:

$$\boldsymbol{M}\ (\boldsymbol{kg}) = \frac{\boldsymbol{Input\ Energy}\ (\boldsymbol{kWh})}{\boldsymbol{NCV}\ (\frac{\boldsymbol{kWh}}{\boldsymbol{kg}})} \qquad \text{(Equation 4.12)}$$

Where;

NCV is the Net Calorific Value. The NCV of firewood is 16 MJ/kg that makes it at 4.44 kWh/kg

Carbon emission saving, $ER = M \times EF$ (Equation 4.13)

According to DEFRA (2010), the carbon emissions factor, EF_W of wood fuel is **183.9 kg** CO_2 per ton of wood fuel.

Table 4.1.11: The daily amount of wood fuel replaced by biogas and CO2 emission reduction

	Input for firewood (kWh/day)	**Amount of firewood replaced (kg/day)**	**Reduction of wood fuel CO2 emission (kg/day)**
General average	448.65	101.05	18.58

Table 4.1.12: The yearly amount of wood fuel replaced and CO2 emission reduction

	Input for firewood (MWh/year)	**Amount of firewood replaced (Ton/year)**	**Reduction of wood fuel CO2 emission (Ton/year)**
General average	163.76	36.88	6.78

4.2. DISCUSSION

Table 5.13 shows a summary of results obtained from sizing of the digester and the expected outputs resulting from operation of the biogas digester. The expected outputs include daily gas production, daily energy production, fuelwood offset and annual carbon emission saving.

Table 4.2.1: Results obtained from sizing of the digester and the expected outputs resulting from the operation of the biogas digester

Items	**Unit**	**Result**
Volume of digester	m3	9.80
Volume of gas holder	m3	6.53
Daily Gas produced	m3 / day	10.88
Energy produced	kWh / day	65.26
Wood fuel offset	kg / day	101.05
Annual Carbon emission saving	Ton / year	6.78

4.2.1. Biogas plant size

The major aspects of the size of the biogas plant are the size of the digester and the gas holder. The substrate available and the gas production per day were assessed and the appropriate digester and gasholder size for the selected group of households in BEAGO were found to be **9.80 m^3** and **3.90 m^3** respectively. The daily gas production was found to be **6.49 m^3 day^{-1}**. At this capacity, the gasholder provides enough storage for the biogas without any wastage. Seen the structure of the plant and to avoid any plug during operation regarding the primary size the household waste, it was requested to shred the biowaste collected for biogas production so that the substrate can be well flushed into the digester from the mixing pit.

The biogas digester can hold the slurry composed of water and the shredded organic waste for 30 days which is sufficient enough to exhaust the biogas content of the slurry before it flows in to the effluent storage tank where it is kept as solid fertilizer for agriculture in the village.

Moreover, one information which interested the population beside of the biogas is to know the lag time before starting to harness the biogas in the gas holder. For that, many experiments have been done to determined that lag time however no standard time was established for that. Nevertheless, a range was established by (Khalid A., 2011) in the case of household waste as being **9 to 12 days** before harvesting the biogas for the need of the targeted population in BEAGO.

4.2.2. Daily gas and energy production

The gas production rate of the biogas plant was estimated at **10.88 m^3 day^{-1}**. The biogas produced can provide useful energy up to **65.26 kWh / day** using a conventional biogas stove with 55% energy efficiency. The biogas is therefore able to replace **101.05 kg** of wood per day for the group of households that means in average **4.59 kg** of wood offset per day per household in the selected group which previously used the traditional three stone stove of 8% efficiency as mentioned before. Therefore, the report of the direction of salubrity and environment ministry in 2011 revealed that 87% of households use firewood or charcoal with 2 kg of charcoal or 6.65 kg of firewood per day (MSECI, 2017) based on the data for a household with an average population of five persons and average per capita consumption of 1.33 kg wood per day (IEA, 2017). Thus, he biogas potential of per household from mixed vegetable/fruit/food waste is therefore able to meet up to **69.02%** of the household energy for cooking.

4.2.3. Environment safeguarding

The first advantage which is gained from the implementation of this project is the amount of methane that will be caught through burning the biogas produced by the plant. The share of methane as being set at **60%** for the household waste and for a daily production of 10.88 m^3 of biogas therefore, the amount of methane emission saved is **6.49** $\mathbf{m^3}$ per day or **2368.85** $\mathbf{m^3}$ per year. This amount of methane is Important for the environmental safeguard knowing the effect of methane as GHG that is estimated at about 21 times of that of Carbon emission.

The research found out that the implementation of this biogas project in BEAGO results in annual carbon emission savings of **6.78 tons**. The carbon emissions saving from biogas projects vary depending on the fuel replaced by biogas and the efficiency of the stoves used.

<u>CHAPTER 5</u>: CONLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

The aim of this work was to present biogas as an optimal solution to the poor household waste management met in Abidjan city. In fact, the major problems related to the interest to implement such a project are the poor management of waste and the unawareness about the issue of clean energy mainly people from rural and remote area. That’s why the study has consisted to select a zone in one of the most vulnerable areas and the choice was made on a group of households composed of **22 households** to make it a small community in BEAGO village located in Yopougon. This community generates **108 kg** of waste per day wherefrom the organic fraction to be used for biogas production is **63.03 kg** for assuring the availability of the feedstock in the area**.** The use of that organic was done to determine clearly the amount of gas that can be harness from the waste produced in the households. The case of the selected area has shown an amount of **10.88 m^3** of biogas that is expected to be produced per day. This production allows the households of the selected area to take off the use of **4.59 kg** of firewood per day per household representing **69.02%** of the total energy need per household for cooking which leads to reduce **4.05 tons** of CO_2 per year.

Beside of this aspect, the methane contains in the organic waste dumped at landfill and uncontrolled disposal in the village is very harmful for the environment so through the biogas production it is burned for the daily need of the population. Thus, this project leads to conciliate the environmental aspect to the technical due to the fact that anaerobic digestion produced a clean gas which will be used for cooking in the selected area. As for the digestate obtained after the process of AD, it will be used as fertilizer for the farms in the village. This study has revealed that the well working of AD technology for rural community through harnessing the energy potential contained in their own waste instead of leave people dump their waste onto uncontrolled disposal which leads to emission of CH_4 from landfilling over the time. Moreover, it is benefit for people living in rural area who use firewood at most to meet their energy need for cooking so that they will be safe from diseases caused by the abundant smoke from the used of wood as fuel since the stove used for that is very less efficient.

Therefore, through the application of AD for the valorization of the organic waste produced from the households in Abidjan, we can achieve some major goals among the UN SDGs such access to clean energy with biogas production then protection of environment through the use of organic waste which the major source of pollution in the area with the flow of lixiviat provided from the landfill et spread a bad smell and finally food security through the digestate obtained at the end of the process of AD which can be used as fertilizer so leads to increase the harvest in the agriculture and secure food supply for the population.

Regarding all those aspects previously mentioned, biogas production for communities can be considered as an optimal solution for the mentioned problem in the city even if the cost benefit remains unknown for this study.

5.2. RECOMMENDATIONS

This study has been done with the materials obtained after a survey made in the selected area and can be used as a sample for further studies. Anaerobic digestion is a large technology for biogas production which uses several types of waste to produce gas. A part of the household waste, other sources of waste generation are very critical regarding the environmental safeguard.

For further studies, it is recommended to expand such a project to a large scale seeing that the technology is still unknown for the Ivoirians and their carelessness for clean energy production. Regarding the general amount of waste produced in the municipality of Yopougon a large station of biogas production will alert people over the country about the possibility and importance of their own waste.

Also, it will be important to be oriented toward the industrial waste which still remains a critical concern for the industries. A deep research is to be done to well valorize that waste which could be rich in biogas potential.

Moreover, this study being focused on the household is to be extend to other sources like bakeries, restaurants, hospital etc…

Finally, the government has to promote the application of self-production of energy through available and inexhaustible sources for the case of biogas, the source is harmful for environment so it should be a priority to show to people the benefit for them to use that technology.

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APPENDIXES

QANTITE EN KILOGRAMME D'ORDURES MENAGERES COLLECTES DANS LA COMMUNE DE YOPOUGON EN 2016 ET 2017

MOIS	2016	2017
Janvier	16,092,440	19,680,880
Février	16,001,820	17,254,460
Mars	14,710,720	22,133,900
Avril	16,231,800	17,541,080
Mai	15,892,560	17,244,240
Juin	17,527,878	18,185,980
Juillet	15,254,333	18,805,180
Août	15,513,460	20,564,700
Septembre	22,108,040	18,625,780
Octobre	19,199,720	18,327,850
Novembre	17,822,240	18,902,740
Décembre	21,049,380	24,484,360

TOTAL (KG)	**207,404,391**	**231,751,150**
TOTAL (TONNES)	**207,404**	**231,751**

RECAPITULATIF DES DONNEES DE DECHETS RELEVEES AUPRES DES MENAGES DE LA ZONE CIBLE DE BEAGO

Quatier	Fermentescible (%)	Plastiques (%)	Papiers et cartons (%)	Tissu (%)	Sable bois cendres graviers (%)	Verre (%)	Métaux (%)	Autre (Composites et spéciaux) (%)
07-05-18	65.53	9.54	7.02	2.64	10.74	1.77	1.79	0.98
08-05-18	55.53	12.93	14.14	2.77	12.14	0.85	0.92	0.73
09-05-18	49.33	11.33	8.95	9.10	17.65	1.10	1.54	0.99
10-05-18	58.77	11.26	12.26	6.12	7.15	2.29	1.10	1.05
11-05-18	58.86	13.89	6.69	1.10	16.16	1.10	1.10	1.10
12-05-18	60.83	13.60	11.53	2.64	7.23	1.10	1.90	1.17
13-05-18	59.82	13.48	11.79	2.05	9.76	1.10	1.10	0.89
14-05-18	35.20	27.17	11.51	5.10	17.65	1.10	1.10	1.18
15-05-18	62.35	11.85	13.05	1.10	6.23	1.10	3.48	0.84
16-05-18	63.21	12.26	6.94	3.10	11.32	1.10	1.10	0.96
17-05-18	55.30	12.59	11.54	9.32	6.58	1.10	1.77	1.80
18-05-18	61.23	15.32	9.73	2.36	7.98	1.10	1.10	1.18
19-05-18	54.03	21.90	13.10	1.10	6.79	1.10	1.10	0.88
20-05-18	66.39	11.42	7.89	1.10	4.53	2.78	3.65	2.24
21-05-18	62.58	11.95	10.44	1.65	10.05	1.10	1.10	1.13
Moyenne Générale	**57.93**	**14.03**	**10.44**	**3.42**	**10.13**	**1.32**	**1.59**	**1.14**

COMPUTATION IN EXCEL

1- Basic computation of daily biogas production

Waste production rate = 0.80 kg /capita/ day
Population = 136
% TS = 27.14
Density = 775 kg/m3
%VS in TS = 94.9
HRT (days) = 30
Water part = 3
T°C = 26.4
Biogas Potential = 0.670 m3/kg VS

Dates	Fermentable (%)	Biowaste for biogas production (kg) during 2 weeks	Volume of biowaste (m3)	Subtrate Volume (m3)	Active volume (m3)	TS (kg)	VS (kg)	S (kg VS/m3 OM)	OLR (kg VS / m3 reactor)	Biogas daily production (m3/day)
07-05-18	65.53	71.29	0.0920	0.3680	11.04	19.35	18.36	49.90	1.66	12.3029
08-05-18	55.53	60.42	0.0780	0.3119	9.36	16.40	15.56	49.90	1.66	10.4265
09-05-18	49.33	53.67	0.0693	0.2770	8.31	14.57	13.82	49.90	1.66	9.2617
10-05-18	58.77	63.94	0.0825	0.3300	9.90	17.35	16.47	49.90	1.66	11.0333
11-05-18	58.86	64.04	0.0826	0.3305	9.92	17.38	16.49	49.90	1.66	11.0510
12-05-18	60.83	66.18	0.0854	0.3416	10.25	17.96	17.05	49.90	1.66	11.4208
13-05-18	59.82	65.09	0.0840	0.3359	10.08	17.66	16.76	49.90	1.66	11.2316
14-05-18	35.20	38.30	0.0494	0.1977	5.93	10.39	9.86	49.90	1.66	6.6084
15-05-18	62.35	67.84	0.0875	0.3501	10.50	18.41	17.47	49.90	1.66	11.7062
16-05-18	63.21	68.77	0.0887	0.3550	10.65	18.66	17.71	49.90	1.66	11.8677
17-05-18	55.30	60.17	0.0776	0.3105	9.32	16.33	15.50	49.90	1.66	10.3826
18-05-18	61.23	66.62	0.0860	0.3438	10.32	18.08	17.16	49.90	1.66	11.4959
19-05-18	54.03	58.78	0.0759	0.3034	9.10	15.95	15.14	49.90	1.66	10.1441
20-05-18	66.39	72.23	0.0932	0.3728	11.18	19.60	18.60	49.90	1.66	12.4647
21-05-18	62.58	68.09	0.0879	0.3514	10.54	18.48	17.54	49.90	1.66	11.7494
General average	57.93	63.03	0.0813	0.3253	9.76	17.11	16.23	49.90	1.66	10.88

2- Energy calculation and environmental analysis

Biogas Energy Content = 6 kWh/m3

Efficiency biogas stove = 0.55 Efficiency of three stones stoves = 0.08

Firewood energy content = 4.44 kWh/kg

EFw = 183.9 g/kg (kg/ton)

Dates	Biogas daily production (m3/day)	Energy produced (kWh)	Power (kW)	Output for biogas stove	Input for firewood	Saved firewood (kg)	CO2 emitted from firewood (kg)
07-05-18	12.3029	73.8173	3.08	40.60	507.49	114.30	21.02
08-05-18	10.4265	62.5590	2.61	34.41	430.09	96.87	17.81
09-05-18	9.2617	55.5702	2.32	30.56	382.05	86.05	15.82
10-05-18	11.0333	66.1999	2.76	36.41	455.12	102.51	18.85
11-05-18	11.0510	66.3058	2.76	36.47	455.85	102.67	18.88
12-05-18	11.4208	68.5250	2.86	37.69	471.11	106.11	19.51
13-05-18	11.2316	67.3895	2.81	37.06	463.30	104.35	19.19
14-05-18	6.6084	39.6505	1.65	21.81	272.60	61.40	11.29
15-05-18	11.7062	70.2372	2.93	38.63	482.88	108.76	20.00
16-05-18	11.8677	71.2060	2.97	39.16	489.54	110.26	20.28
17-05-18	10.3826	62.2954	2.60	34.26	428.28	96.46	17.74
18-05-18	11.4959	68.9756	2.87	37.94	474.21	106.80	19.64
19-05-18	10.1441	60.8648	2.54	33.48	418.45	94.24	17.33
20-05-18	12.4647	74.7883	3.12	41.13	514.17	115.80	21.30
21-05-18	11.7494	70.4963	2.94	38.77	484.66	109.16	20.07
General average	10.8765	65.26	2.72	35.89	448.65	101.05	18.58