Mechanisation and Bio-Hydrogen based Hybrid Systems for Fuel Cell Electricity Production from Solidwaste

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Abstract: The increase of world population increases the solid waste. In Lebanon, two years ago, the problem of waste management appeared as one of the big problems to deal with. There is still no final solution for this problem. In this work, we studied different methods for waste management, and we proposed a hybrid system in the aim to optimize the solution by decreasing the pollution with acceptable price.

Our system uses the gasification technique to produce synthesis gas; consisting of hydrogen and methane, from the daily generated waste. This gas will be then used by fuel cells to produce electrical and thermal energies. An organic waste rate is recovered by anaerobic digestion to produce biogas rich in methane. The thermal energy required for the gasification technique is recovered by cogeneration of the fuel cell and by an additional contribution of the biogas combustion.

This work comes as a solution to two major problems in the Lebanon: the first one is the management of household waste and the second is the insufficient electrical energy produced. Our method increases the electrical efficiency and decreases the CO2 emission in comparison with traditional organic waste treatment methods. Additionally, using our method, we will be able to produce enough electricity to serve more than 38,000 houses at low CO2 emission using the waste generated by Tripoli.

Keywords: *Gasification; Fuel cell; Methanisation…*

I. INTRODUCTION

Since the beginning of the century, global energy consumption has been growing strongly in all regions of the world. It seems that, tangentially, energy consumption will continue to increase, under the effect of economic growth on one hand, and the increase in electricity consumption per occupant on the other hand. The availability of fossil energy resources, the environmental problems related to energy production and consumption, and dependence on fossil fuels make it necessary to rethink about energy policy and to develop new sources of energy. Renewable energy resources (biomass, wind, solar, hydro, etc...) would produce some of the energy we need while contributing to the reduction of gas emissions [1].

Biomass, the term comprising all organic compounds of non-fossil origin (agricultural, wood, domestic and industrial waste fermentable), is a short reserve of energy existing in the form of organic carbon that could be recovered by specific processes depending on the type of constituent. The energy recovery of organic waste by a gasification process is used to produce a gas rich in hydrogen and carbon monoxide called synthesis gas. This gas is well suited to be a fuel for fueling gas turbines, internal combustion engines or fuel cells which have very large efficiencies compared to the other two.

II. PROBLEM IDENTIFICATION AND BASIC PRINCIPLE

Due to the existence of the old waste immersing in land in most of the underdeveloped countries, and untreated organic fresh waste, we are thinking of using a hybrid system of two types: gasification and methanisation. Additionally, we use the fuel cell as an electric generator that can consume the obtained product with good performance.

Thus, a system grouping gasification and fuel cell perfectly meets the dual problem of lack of energy and disposal of old waste for gasification and fees for methanisation [2].

III. METHODOLOGY OF BIOMASS ENERGY VALORISATION

Biomass, a term that includes all organic compounds of non-fossil origin (agricultural, wood, domestic and industrial waste…), is a short supply of energy existing in the form of organic carbon. The advantage of energy conversion of biomasscompared to other renewable energy sources is that we have more energy production and biomass actively participates in the treatment of organic waste thus contributing to the reduction of environmental impact. Biomass energy conversion processes are essentially based on two families of conversion processes: the biochemical pathway and the thermochemical pathway [3].

• The biochemical pathway uses microbial and enzymatic action to degrade biomass. Anaerobic digestion is the transformation of biomass into biogas by a complex natural microbial community present in fresh organic matter.

• The thermochemical pathway combines several processes based on the cracking of biomolecules under the effect of heat: combustion, pyrolysis, gasification can be used in heat generation [4].

A. Gasification principle

The gasification of biomass is a thermochemical transformation that converts a solid fuel into a synthesis gas rich in hydrogen (H_2) and carbon monoxide (CO) in the presence of a gasifying agent (O_2, air, CO_2, steam of water ...). Independently of the gasification device, the same thermochemical processes are involved, such as: drying, pyrolysis, combustion and gasification [8].

• **Drying**: At first, the moisture present in the product will evaporate. This endothermic phase occurs at a temperature below 200 ° C.

$$\text{Wet biomass} \rightarrow \text{Dry biomass} + H_2O$$

• **Pyrolysis**: Pyrolysis is a transformation in the absence of oxidizing products. Under the action of heat, it breaks down biomass into three main phases [12]:

1) A non-condensable gaseous fraction: which essentially comprises H_2O, CO, CO_2, H_2, CH_4, C_2H_4, C_2H_2 and other heavier hydrocarbons.

2) A condensable gaseous fraction: which contains oils composed of water, organic species and several inorganic species essentially composed of Ca, Si, K, Fe, Na, S, N, P, Mg and heavy metals.

3) A solid residue: the char (coal), mainly composed of carbon. The amount, composition and properties of pyrolysis products differ depending on the operating conditions, in particular the temperature and the heating rate.High temperatures (> 700 ° C) ensure the conversion of biomass into gas, while at lower temperatures (<500 ° C) coke is mainly formed.

• Combustion: The volatiles, group condensable gaseous and incondensable gaseous species, produced during the pyrolysis phase will oxidize using a sufficient supply of air. Their combustion makes it possible to reach high temperatures and to bring energy into the reactor.

• Gasification: This gasification phase is initiated under the effect of high temperatures (> 800 ° C) and differs from pyrolysis by the addition of a gaseous reactant which may be oxygen, product or combustion products (CO2, H2O). The difference with the combustion is the amount of oxygen introduced that is less than the amount required for total oxidation of the biomass.

B. Anaerobic digestion

Principle: Anaerobic digestion is the transformation of organic matter into biogas (mainly methane and carbon dioxide) by a microbial community that functions in anaerobiosis [11].

This transformation widely existing in nature is found in swamps, intestines of animals, insects ... and very generally when storing organic matter in the absence of oxygen.

The classical scheme identifies four transformation steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

• Hydrolysis: This phase concerns the degradation of complex organic molecules into monomers. Compounds such as polysaccharides (such as cellulose), proteins, and lipids are hydrolyzed to simple sugars, amino acids and glycerol and fatty acids respectively. This transformation is provided by extracellular enzymes.

• Acidogenesis: This phase converts the various monomers resulting from hydrolysis into short chain organic acids (2 to 6 carbons); the main acids produced are acetic acid, propionic acid and butyric acid. Other co-products are also generated such as carbon dioxide and hydrogen, as well as ammonia nitrogen (as NH4 + or NH3) in the case of protein hydrolysis.

• Acetogenesis: The acetogenesis step covers the transformation of a small number of simple compounds into acetate, bicarbonate and hydrogen. The bacteria that perform this step are referred to as the Hydrogen Producing Bacteria (OHPA). However, the accumulation of hydrogen blocks their development and it must be eliminated. This elimination is carried out either by methanogenic bacteria consuming hydrogen or by sulphate-reducing bacteria (reduction of sulphates to sulphides). The group of acetogenic bacteria is often referred to as syntrophic bacteria.

• Methanogenesis: The methanogenic species mainly use as substrates acetate, carbon dioxide and hydrogen. Their growth rate is lower than that of acidogenic bacteria. The most common methanogenic species are generally divided into two groups:

1. Acetotrophic methanogens that is responsible of 70% of methane production in digesters using acetate.

2. Hydrogenotrophic methanogens that use hydrogen and carbon dioxide.

IV. CHOICE OF MAIN PROCESSES TO FORM OUR HYBRID SYSTEM

The purpose of the system is to produce electricity by the fuel cells. Before selecting the processes that transform waste into biogas to feed the fuel cells, let us show the fuel cell used in our system.

*A. The fuel cellSOFC (***Solid Oxide Fuel Cell)***:*

The choice of fuel cell is done according to the following features:

• The electrical efficiency.
• The electric power supplied.
• The range of feed gases acceptable.
• The temperature of the exhaust gases.

The efficiency of a SOFC fuel cell coupled with a gas turbine (CHP system) may exceed 80-85%. With a maximum power up to 500 MW.

The SOFC fuel cellsdisplay some particularly interesting features:

• The advantage of being able to use in addition to pure hydrogen, many fuels such as natural gas, diesel, carbonated coal and biogas,

• Emission of gas: no NOx, low CO2.
• Their power can range from kilowatts to megawatts.
• A wide variety of geometries and architectures.

This type of fuel cell is currently of great interest given its current and potential performance and its insensitivity to carbon monoxide, which becomes a fuel [14]

The principle of operation: It is an electrochemical and controlled redox of hydrogen and oxygen with simultaneous production of electricity, water and heat, according to the following overall chemical reaction, known as:

$$H2 + ½ O2 \longrightarrow H2O + 2e$$

Components: electrodes, interconnect plates or bipolar plates, catalyst, electrolyte, interconnections.

B. The gasification process (Pearson): The choice of the gasification process of waste treatment should be based on the following conditions [5, 6, 8]:

- The synthesis gas should be rich in hydrogen.

- The synthesis gas produced must be a PAC feed gas without causing any risk of operation for the fuel cell.

However, the fuel cells chosen (SOFC) accept CO and methane as feed gas, so a synthesis gas rich in CO and CH4 is also appreciated, and this reduces stress. A very wide range of gasification processes exist.

It’s found that the Pearson Technology process is the most favorable. This process involves the conversion of organic waste into high quality synthesis gas rich in H2 (51.5%), this process uses water vapor as an oxidizing agent and it is a good advantage. However, water vapor improves carbon gasification and reforming reactions and thus increases the yield of gaseous products: H2, CO, CO2.

The trained flow gasifier is shown schematically in Figure 1:

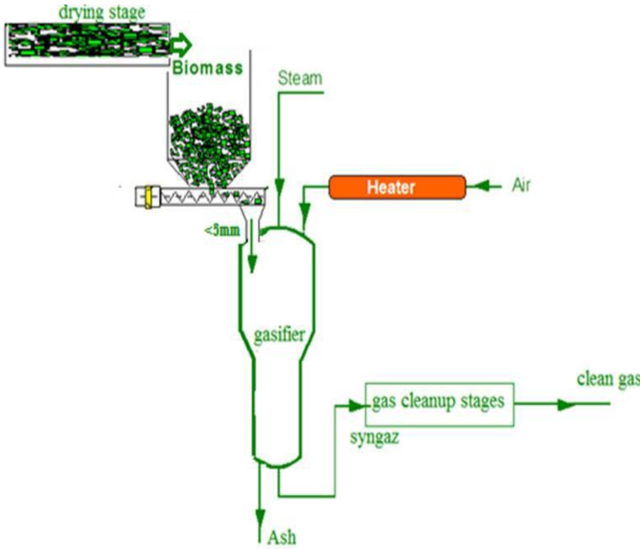

Fig.1Schema of trained flow gasifier [6]

The waste undergoes a pretreatment before introducing it into the gasifier. Indeed, the waste is grounded to fine particles (<5mm) and dried (15% humidity). In the gasifier, the temperature is maintained at 1200 °C. After recovery of synthesis gas, the synthesis gas undergoes 5 stages of treatment to remove tars and ashes.

The heat recovery of the process is done in the state of synthesis gas and also inside gasifier (25.9%) by introducing water through the exchanger [6].

***C. Anaerobic digestion process (DRANCO technology)*:**

The interest of anaerobic digestion in this project is the production of biogas in order to burn it to offset the heat energy demand at the level of gasification.

The DRANCO process [4, 7], marketed by OWS (Organic Waste Systems), is an advanced biotechnological process for the treatment of organic waste derived from household waste.

DRANCO is a reliable and recognized anaerobic digestion technology [4].

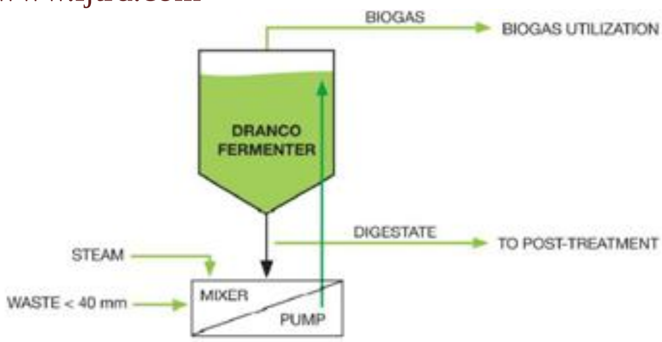

Fig. 2Principal function of digester DRANCO [4]

The waste undergoes a pretreatment before entering the digester; in fact the organic waste is reduced in size to a size less than 40 mm. The organic fraction is then mixed with a large amount of digested residues. A small amount of water vapor is added to the mixture to raise the temperature of the mixture to 50-55 °C. The preheated mixture is then pumped up the digester through feed tubes (Figure 2)

The biogas is recovered through the roof and flows to storage and processing stages. The digested residue is extracted from the bottom of the digester. Most of the extracted material is recycled to the process and screwed to the mixing portion of the pump for mixing with incoming fresh feed. The remaining part (digestate) is diverted to another treatment. The average residence time in the digester is about 20 days.

V. OUR NEW HYBRID SYSTEM

The Tripoli landfill receives 400-450 tonnes/day of mixed solid waste (household waste, construction and destruction waste). In Tripoli 60% of solid waste is organic and this is an advantage for gasification [10].

The diagram presented in Figure 3 shows the waste treatment steps in the new hybrid system from sorting to electricity generation:

1. The sorting of waste that gives us an organic waste stream of 2.77 Kg/s. This flow will be treated by two ways of energy recovery of the waste: 2 kg/s will be treated by gasification and 0.77 kg/s by anaerobic digestion.
2. Waste treatment:

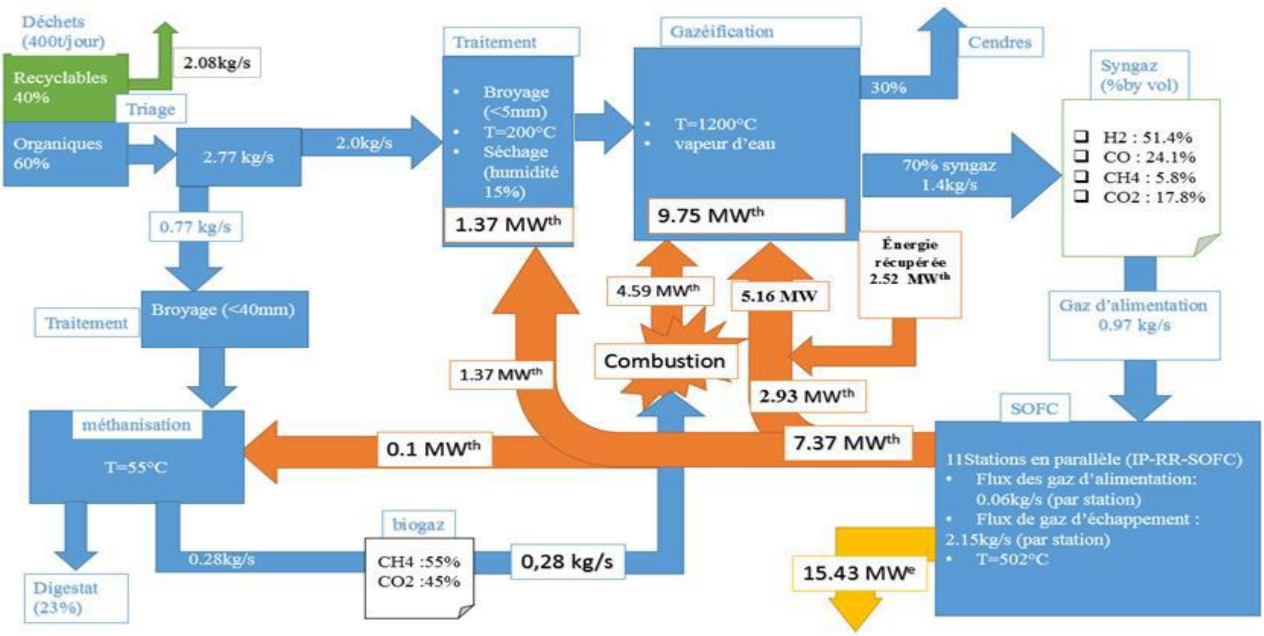

Fig.3 Diagram of the new hybridsolid waste treatment, from sorting to electricity generation

a. For gasification: grinding to obtain a size less than 5mm and drying up to 15% moisture. This step takes its heat contribution from the energy recovered from the exhaust gases of the batteries.
b. For anaerobic digestion: grinding to obtain a size less than 40mm

3. Gasification in a flow gasifier driven by Pearson technology requiring 9.75 MW thermal. The synthesis gas flow is 1.4 kg/s. The thermal efficiency of this process is 70% and allows the recovery of 25% of this heat at a temperature of 1200 °C, this energy is used to superheat the exhaust gas before entering the gasifier.
4. SOFC fuel cells responsible for generating electric current from synthesis gas. We will need 11 IP-RR-SOFC parallel stations producing 15.43 MW electric ready to be sent to an electric grid. 7.37 MW are evacuated in thermal form in the exhaust gas, this energy is used in the gasification stage, methanisation and drying.
5. Methanisation in a digester by Dranco technology. The methanisation of waste led to the production of a biogas with a flow rate of 0.28 kg/s used for the heating of gasifier by combustion.

VI. COMPARISON WITH OTHER PROCESSES

Table 1 shows the difference between our hybrid solution and other studies done for electricity generation from incineration and gasification.

Table 1 Comparison of the new hybrid system with traditional methods of treatment: methanisation and incineration [10,11,12].

process	Hybrid system	Hydrogénation	methanisation	Incineration
Power (MW)	15.43	8.46	4.8	30
Yearly production (TWh/years)	136.1	74	42	262.8
CO2 emission (Ton/years)	49.99	58147	7,89,200	2, 086,522

The results shown in the table demonstrate that, from a power point of view, incineration is the most profitable with a generated power of 30 MWe, but with significant CO2 emissions (2,086,522 tons / year)[10]. Although the power produced by the hybrid system is lower than that of incineration but it releases 2.4% of the amount of CO2 released by the latter.

Note that the output power and the CO2 emissions of the hybrid system is better than themethanisation and hydrogenation systems with lower CO2 emissions.

CONCLUSIONS

The energy recovery of solid waste bythe proposed hybrid system composed of gasification and anaerobic digestion is quite important. Our study in this system provide the following important results:

1. High efficiency of treatment processes.
2. High conversion efficiency in electricity
3. Possibility of transmitting gas for use in other areas (eg. transportation)
4. Regeneration of heat produced in the system
5. Negligible CO2 emissions rate.

References

[1] Claudine, C. (2016) Déchets - Prétraitement - Traitement – Valorisation, ADEME.
[2] POLLIER, K.(2013) Tendances de l'efficacitéénergétique au Liban, Association Libanaise pour la Maitrise de l’Energie et de l’Environnement, ALMEE.
[3] BUFFIERE, P. CARRERE, M. LEMAIRE, O. VASQUEZ, J. (2007)Guide méthodologique pour l'exploitation d'unités de méthanisation de déchets solides, Projet METHAPI-Expertise.
[4] Luc De B. (2012), the dranco technology: a unique digestion technology for solid organic waste,Organic Waste Systems nv.
[5] Collard, Francois-Xavier, (2012).Nouvelles stratégies catalytiques pour la gazéification de la biomasse: influence de métauximprégnés sur les mécanismes de pyrolyse.PHDReport, Compiegne.
[6] Taylor, R. H. Jo, Bauen, A. (2009)Review of technologies for gasification of Biomass and wastes.Report, E4Tech.
[7] Williams, Robert B. (2008) Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste.Report, California Integrated Waste Management Board, California.
[8] Lamarche P.,(2011) Contribution à l'étudeexpérimentale et à la modélisation de la gazéificationétagée de la biomasse en lit fixe, PHD report.
[9] Rehmet, C. (2013) Étude théorique et expérimentale d’une torche plasma triphasée à arcs libres associée à un procédé de gazéification de matière organique, PHD report.
[10] Bacha, R. K. Dit. (2015) Décharge de Tripoli Station Bio-hydrogène,Master report ULF.
[11] Chavez-Vazquez, M. and Bagley,D.(2002) Evaluation of the performance of different anaerobic digestion technologies for solid waste treatment, CSCE/EWRI of ASCE Environmental Engineering Conf., Niagara.
[12] Antoni, G. Hazi, M.(2004) Pyrolyse-Gazéification de déchets solides, PROCEDIS.
[13] Jonathan,R.(2014) Kinetic Modeling and Experimentation of Anaerobic Digestion, Massachusetts Institute of Technology, MIT.
[14] Haberman, B.A. Young,J.B.(2004) Three-dimensional simulation of chemically reacting gas flows in the porous support structure of an integrated-planar solid oxide fuel cell, International Journal of Heat and Mass Transfer, Volume 47, Issues 17–18, Pages 3617-3629.
[15] Goettler, R. (2009) Overview of the Rolls-Royce SOFC Technology and SECA Program,Rolls-Royce Fuel cell development.
[16] Ando, Y.Kabata, T.(2007) Solid-oxide fuel cell system for megawatt scale stationary power generation,Inc., Rolls-Royce Fuel Cell Systems (US).

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