An Agent-based System to Monitor an Energy Biomass Process

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***Abstract*—This research is the study of a project, promoted by the Italian Ministry of Education, University and Research under the protection of the European Community, in a more complex "Smart Cities" project, devoted to the realization of an alternative system for green energy production. The system consists of an electrical power supply generated from the anaerobic digestion of biomass. It also includes the storage of electrical energy in a superconducting magnetic energy storage device in order to overcome energy blackout and meet the energy needs of the network when the demand rises in closed-cycle production systems. Finally, an agent platform of remote control should monitor the whole system in the future.**

I. Introduction

The Earth has undergone over the century significant changes due to Mankind. Because of this the global consumption of natural resources has exceeded their availability. Human population growth has given rise to a serious problem of energy supply. Most of the world energy requirement is satisfied by fossil fuels, a non-renewable energy source.

Biomass is a renewable, perpetual energy resource, which can supply human energy needs in a sustainable way. Biomass is also a generic term for all vegetable materials storing solar energy through photosynthesis. During photosynthesis, the solar energy absorbed by plants is converted into carbohydrates and oxygen through the utilization of the carbon dioxide already present in the air and the water, but the use of vegetable material in the biomass transformation process can be considered an unlimited resource only if its rate of consumption does not exceed its rate of biological regeneration. Therefore, for every vegetable species used in biomass production, there is an inherent limit which depends on the size of the field where it is grown, besides climatic and environmental variables. Therefore, biomass processing for fuel purposes requires large areas of land.

Environmental conditions, such as temperature and the availability of water, influence biomass seasonality. The use of biomass to produce energy can be considered advantageous when the growth of the vegetable species is thick and vigorous and its availability during the year is sufficiently constant.

In the following, a biomass energy plant is presented. The complete system, which includes an anaerobic digester, a co-generator and a superconducting magnetic energy storage system, is monitored by a sensors network [1].

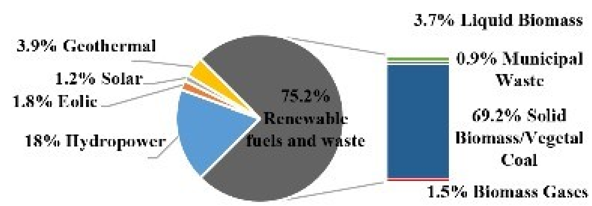

Fig. 1. Percentage distribution among renewable energy sources in 2011.

The actual prototype system furnishes 10 kW of power for 1 minute but, currently, it does not take advantage from the benefits coming from the adoption of the agent technology[1], particularly in terms of mutual coordination among the many components exploited to rule this complex process, of the modular approach intrinsic into the agents and from the possibility to exploit reliable and consolidated communication standards (very useful in presence of heterogeneous components). Therefore, the next step in the evolution of this project consists in monitoring, managing and coordinating all the system components by means of intelligent software agent belonging to a multi-agent system appositely designed to this aim.

The paper is organized as follows. In Section II the monitoring activity of the realized by the software sensor agents is described, while Section III provides a description of the biomass plant structure. The sensor agent monitoring system is introduced in Section IV. Finally, in Section V some conclusions and future scenarios are drawn.

II. Energy and Renewable Sources

Only 13.3% of the energy produced on Earth comes from renewable sources. Fossil products (such as petroleum, coal and natural gas) plus nuclear sources meet 81.6% and 5.1% of worldwide energy needs, respectively [9].

About 75.2% of the total primary energy production from renewable sources comes from biomass [10] as shown in Fig.1

Biomass solves the problem of waste disposal and reduces net carbon dioxide emissions. Biomass is a raw material

[1]The interested reader might refer to an overwhelming number of surveys dealing with different scientific areas that take advantage from the agent technology [2]–[8].

which can be converted into gas, liquid and solid energy, and then further processed in order to generate electricity and heat. Biomass-to-energy conversion technologies include direct combustion, co-combustion, cultivated biomass-to-liquid fuel conversion, and biogas production. Direct combustion of biomass produces heat for industrial and domestic use, electricity and gas which can be used as a driving force.

In order to monitor the processes involved in the storage and digestion of the biomass that produces biogas, locally a software *sensor agent* should monitor the biomass cells in order to maintain the working conditions and communicate to its agency when the specified conditions become altered. Parameter monitoring is carried out in the liquid and gas phases, ensuring early detection of changes in the parameters that are indicators of the proper process of digestion. The sensor agent also calibrates the organic load in the digester based on the parameters. The basic characteristics of a sensor agent monitoring system should include the determination of the concentrations of alkalinity, pH, fatty acids, and ammonia. Another very important parameter is that of *Volatile Fatty Acids* (VFAs), the accumulation of which is indicative of some type of instability occurring in the process. These parameters are *Normally detected by Infrared Spectroscopy* (NIRS), by an electronic nose, by gas chromatography and by means of biosensors, which should be managed by the sensor agent.

In particular, the measurement of the concentration of biogas produced is a reliable method of monitoring the digestion phase. Thermal conductivity sensors are used for separate measurements of methane and carbon dioxide; these are composed of two thin coils covered with platinum and are relatively fragile.

The infrared sensors are used to simultaneously assess the concentration of methane and carbon dioxide, even though they are very expensive and require a complex electronic configuration [11]. In order to monitor a process of the anaerobic digestion of waste of food origin, it is sufficient to provide for the evaluation of parameters such as temperature and alkalinity, besides the concentration of ammonia and VFAs.

III. Biomass Plant Structure

A. Production Chain

Biogas plants comprise several technological components divided into operational units, see Fig. 2

Anaerobic digester reactors are made of the reinforced concrete or steel, and include several components designed to re-create the ideal conditions for the biochemical reactions that lead to the production of biogas.

B. Anaerobic Digestion Process

The degradation of organic substances and their subsequent conversion into biogas can vary from 40% to over 95%, depending on the type of biomass used, the processing conditions and the time necessary for the degradation process. Biomass that is rich in fats and proteins, as compared to

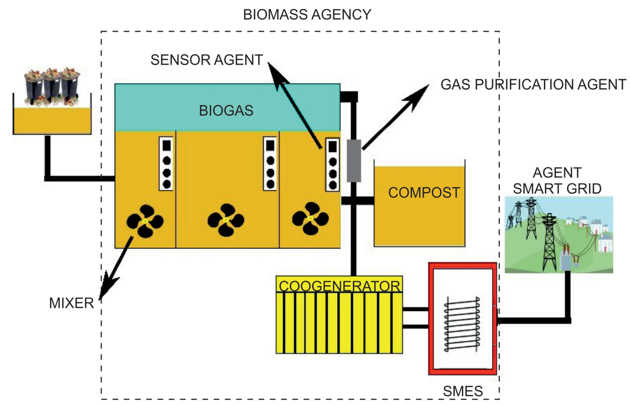

Fig. 2. Production process of a biomass plant.

carbohydrate-rich biomass, has a positive effect on the production of methane. Anaerobic digestion involves different microbic groups interacting with each other which include hydrolytic bacteria, acidifying bacteria (acetogenic and homoacetogenic) and methanogenic bacteria that are responsible for producing methane and CO_2. The microorganisms, which cause the biological degradation of organic matter, according to the temperature range where they act, are divided into Psychrophilic (temperatures below $20°C$); Mesophilic, (temperatures ranging from $25°C$ up to $45°C$) and Thermophilic, (temperatures above $45°C$).

Due to the slowness of the anaerobic reactions in the psychrophilic field (temperatures $< 20°C$), the process is normally performed in mesophilic ($30°C$ – $35°C$) or even thermophilic (efficient values around $55°C$ – $60°C$) ranges.

Methane-producing bacteria can only live in an anaerobic environment with humidity content of at least 50% in the substrate, and they also require continuous monitoring and control of the other parameters involved in the process.

Depending on the type of gas to be analyzed, there are different kinds of sensor systems. For carbon monoxide and nitrogen dioxide an electrochemical cell is normally used; total organic carbon, however, is determined according to the presence of volatile organic compounds (VOCs) through the use of a photoionization detector (PID).

Another relevant aspect to consider during the monitoring of a biomass energy plant is the analysis of all the parameters involved in the inhibition of bacterial growth, which can limit the transformation of the substrate inside the anaerobic digestion system into the final product. Substances such as heavy metals, salts, residues of pesticides and pharmaceutical products, solvents, etc., can adversely affect the whole process of anaerobic digestion. Moreover, the substrate itself can be a limiting factor because it is able to influence the successive stages of the digestion process.

Attention should be paid to the monitoring of some metabolic intermediates such as propionate, which is a quantitatively important intermediate in anaerobic digesters. Although the concentration of propionate is usually quite low, an increase can prove to be toxic. The toxicity limit for propionate

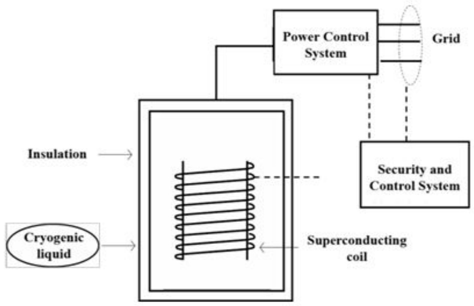

Fig. 3. Block diagram of a SMES system.

appears to be around 3 g/l. The degradation of propionate is also influenced by hydrogen which can inhibit the microbial degradation of ethanol and, reversibly, the growth of abundant anaerobic bacteria. Along more general lines, it has been reported in literature that high concentrations of volatile fatty acids (VFAs) can also have toxic effects, mainly due to the resulting decrease in pH.

C. Storage System

The increasing demand for a high-quality power supply has resulted in a growing interest in the use of high-performance energy storage technology. Superconducting magnetic energy storage (SMES) is able to store considerable amounts of energy within the magnetic field created by an electric current flowing through a superconducting coil maintained below the temperature of superconductivity by means of a cryogenic liquid, as shown in Fig.3. The stored energy is instantly available in the form of electricity and may be unloaded from the superconducting ring at an efficiency of over 95% of the whole charge/discharge cycle.

The two main blocks of the system are the superconducting coil and the cryogenic cooling system. The coil requires the presence of a magnet designed and built to work at cryogenic temperatures. In this way, the critical temperature of the coil, that is, the temperature of transition between the normal and the superconducting state can be maintained within a controllable range. Also, the critical current, which defines the maximum current of transition from the normal to the superconducting state, can be raised to increase the performance of the storage system.

The cryogenic cooling techniques are usually based on nitrogen- or liquid-helium-bath systems, even though the experimental closed-cycle system under investigation allows the achievement of high performance with minimum energy consumption, avoiding contact between the superconducting material and the coolant. Finally, close attention is also paid to the sensors and electronic control systems with a view to reducing losses which, although minimal, may affect the efficiency of the system.

The coil is made of Magnesium Diboride (MgB_2), the characteristics of which are reported in the table I.

Radius	1.13 mm
Number of filaments	36
Composition	Ni 70%, Cu 20%
Critical Current @ 22 K	550 A

TABLE I
MAIN PROPERTIES OF MgB_2 CONDUCTOR.

In the presence of a magnetic field [12], this material can withstand higher temperatures without compromising the operation of the device while subjecting it to less stress.

D. Agent Smart Grid

The realization of an agent smart grid currently is over the aim of this paper, although it is the complement to a renewable energy system as that above described. Therefore, in this section, only a brief description of an agent smart grid approach is provided.

More in detail, an agent smart grid is the evolution of the traditional electrical network in which a set of specialized agents should monitor and coordinate sensors, communication, control and measurement systems allowing them to work together in order to monitor the flow of energy with the aim of overcoming the variability of consumption demands. The implementation of the new-generation agent smart grid networks comes in conjunction with the growing demands for electricity that cannot be met by the enlargement of the old electrical networks, due to economic and environmental problems.

The technology that drives the agent smart grids should make the integration of renewable energy sources of different origins possible, which, because of their dependence on variable phenomena, are discontinuous over time.

A case in point is the management of a sudden drop in voltage by taking current from other districts that are having a low absorption or that can store energy, such as in the case of those with an SMES system. To this end, agent networks connected to a remote monitoring agency play a role of primary importance, allowing the reduction and in some cases the elimination of the load losses of the network and also of the possible interruption of the supply of energy. Moreover, in order to improve their reliability such grids could exploit the benefits of different technologies widely adopted in the multi-agent scenarios [13]–[17]

IV. THE SENSOR AGENT MONITORING SYSTEM

The necessary biological reactions take place inside digesters (anaerobic reactors), where the monitoring of specific parameters is required, in order to ensure the optimal conditions for the working of the entire system. Unfortunately, the different components often presents mutual coupling problems so that the adoption of intelligent software agents could easily overcame them [18]. Specifically, the main current process parameters that agent sensors should control are:

i. Temperature has important effects both on the physical-chemical characteristics of the biomass in the digester and on the microorganisms. For example, it affects the kinetics of the process along with the selection of the bacteria capable of operating in the temperature range selected. It is recommended that temperature fluctuations greater than $\pm 1°C$ – $2°C$ within the chosen temperature range be avoided, because even small changes can significantly affect the outcome of the process.

ii. Volatile Fatty Acids (VFAs) are organic acids produced during the degradation of organic matter. The concentration of VFAs is expressed as the concentration of acetic acid in the material volume (mg/L); it depends on the quantity and the quality of the material loaded into the digester, as well as on the balance between acidogenic and methanogenic bacteria.

iii. Alkalinity represents the system's ability to accept protons, and it is expressed as the concentration of calcium carbonate. The alkalinity of an anaerobic digester is determined by the coexistence of ammonia, originating from protein degradation, and bicarbonate, derived from the dissolution of carbon dioxide in the medium, forming a system able to buffer the lowering of the pH due to the accumulation volatile fatty acids.

iv. Ratio VFA/Alkalinity. The concentration of VFAs and alkalinity are two parameters which are very sensitive to changes in the system, and their ratio is a diagnostic parameter indicating possible conditions of instability. Values of around 0.3 indicate stable operation of the digester, while higher values indicate the accumulation of VFAs and the onset of stability problems. The VFA/Alkalinity ratio has diagnostic significance because it describes the dynamics going on between material already digested (alkalinity represented by ash and ammonia) and new degradation (VFAs). High VFA/total alkalinity ratio values often indicate an overload of the digester [19]–[21].

v. The Carbon / nitrogen ratio (C/N) in the biomass must be between 20 and 40 in order to avoid deficiency or excess of nitrogen.

vi. Concentration of ammonia. Ammonia is produced during the degradation of proteins. A high concentration of ammonia can inhibit both methanogenic and acidogenic bacteria. Concentration ranges:
   - 200 – 1,500 mg/L (never toxic);
   - 1,500 – 3,000 mg/L (inhibitory if the pH is below 7.4);
   - 3,000 mg/L (always inhibitory).

   However, the presence of ammonia is important because it buffers the system inside the digester and it compensates for the accumulation of VFAs, maintaining a stable pH.

vii. pH. This value depends on such parameters as the concentration of VFAs, ammonia and alkalinity. In a stable digester the pH value should be around 6.5 – 8. If the pH value falls below 6.5, then an accumulation of VFAs has occurred, often because the digester has been overloaded.

The gas produced during anaerobic digestion consists mainly of a mixture of methane (CH_4) and carbon dioxide (CO_2) with small amounts of other gases, including hydrogen sulfide (H_2S), hydrogen (H_2), nitrogen (N_2), and low molecular weight hydrocarbons. Typically, the bioreactor contains 50% – 75% methane and 25% – 50% carbon dioxide; the remaining gases are present in very small quantities. The composition of the biogas can vary in terms of concentration depending on the raw material used and the operating conditions.

Component	Volume percentage
Methane (CH_4)	50% – 80%
Carbon Dioxide (CO_2)	50% – 20%
Nitrogen (N_2)	$< 1\%$
Hydrogen (H_2)	$< 1\%$
Ammonia (NH_3)	$< 1\%$
Hydrogen sulphide (H_2S)	$< 1\%$

TABLE II
BIOGAS COMPOSITION.

Since biogas is normally made up of a mixture of gasses, its characteristics must be evaluated in each individual case. However, in many instances, the physical characteristics of the three main constituents, namely, methane, carbon dioxide and hydrogen sulfide, can be used to characterize the biogas.

The temperature of biogas is measured by a stainless steel electrode sensor, which is installed on the wall of the bioreactor, and measures a range of values between $-40 \circ C$ and $135 \circ C$. The probe consists of a 20 $k\Omega$ thermistor, a variable resistor the resistance of which decreases nonlinearly with increasing temperatures.

The interface measures the value of resistance (R) at a certain temperature and converts the resistance using the Steinhart-Hart equation:

$$T = \left[A_0 + A_1 \left(\ln 1000R\right) + A_2 \left(1000R\right)^3\right]^{-1} - 273.15 \quad (1)$$

Where T is the temperature, R is the resistance and A_0, A_1 and A_2 are constants.

The alkalinity of the substrate can be measured by the use of laboratory instrumentation, such as titration, infrared spectroscopy and liquid or gas chromatography. Before being sent to a laboratory for analysis, the sample is pre-treated with reagents. There are also indirect methods to measure the value of alkalinity that make use of sensors and calculation software, and measurements are obtained in real time. This monitoring system uses three types of sensors, pH, redox potential, and electrical conductivity, which are installed on the wall of the bioreactor and monitore by a sensor agent. The data are displayed, stored, and processed by the agent for the calculation of the alkalinity level, according to the following equation:

$$alk = -8906 + (1678 \cdot pH) + (1.998 \cdot redox) + (384.2 \cdot EC) \quad (2)$$

The probe that detects the pH is a sensor electrode characterized by a double junction and a polycarbonate body equipped with a flat glass membrane which makes it durable

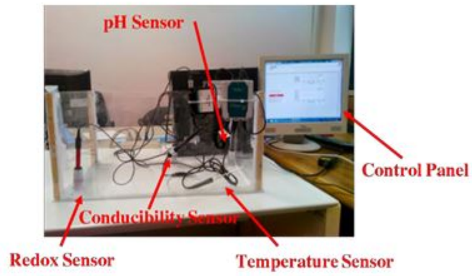

Fig. 4. Experimental digester of the future sensor agent monitoring system.

and easy to clean. The pH probe measures values between 0 and 14. The probe which measures electrical conductivity in order to determine the ionic content of an aqueous solution is characterized by three ranges of work:

- Low Range: 0 to 200 $\mu S/cm$ (0 to 100 mg/L TDS);
- Mid Range: 0 to 2,000 $\mu S/cm$ (0 to 1,000 mg/L TDS);
- High Range: 0 to 20,000 $\mu S/cm$ (0 to 10,000 mg/L TDS).

This probe measures the ability of a solution to conduct electric current between two electrodes expressed in Siemens. The characteristic equation of operation of the probe is:

$$C = GK_c \tag{3}$$

where C is the electric conductivity, G is the conductance and the cell constant K_c is defined by the ratio between (distance between the two electrodes)/(surface values of the electrodes).

The oxidation reduction potential (ORP) probe is composed of electrodes that measure the capacity of a solution to act as a reductant or oxidant. The electrodes are composed of a platinum part immersed in the solution in which the oxidation-reduction reaction takes place, and another part in which the platinum electrode is immersed in a solution of silver chloride which is used as a reference. The probe can measure the redox potential between -450 mV and 1100 mV. The probe that assesses the concentration of ammonia in the bioreactor is made of an ion-selective membrane electrode specific for ammonium NH_4 (ISE). When this membrane electrode comes in contact with a solution containing specific ions, it develops a voltage which depends on the concentration of ions in the solution.

The data measured by the sensors are sent to a computational unit, on which has to run the sensor agent that has to perform all its required tasks of data processing.

Tank-level monitoring was accomplished through the design and realization of a sonar system, which included the fabrication of both transmitter and receiver made in our laboratory with a sheet of polyvinylidene- fluoride (PVDF) as shown in Fig. 5.

By applying an alternating voltage between the two electrodes, the semi-cylindrical geometry and its lateral constraint allows the conversion of longitudinal motion into radial vibration. The PVDF transducer is shown in Fig. 6. It has been

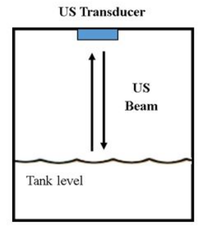

Fig. 5. Tank level monitoring based on PVDF transducer.

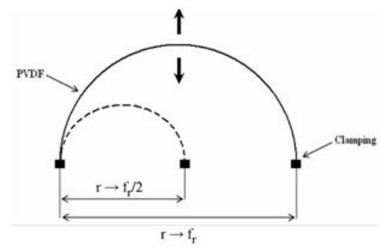

Fig. 6. Piezo-polymer film transducer obtained by curving a PVDF resonator.

properly designed to work in hazardous environments and was fabricated in cooperation with the BATS Company, s.r.l.

The resonance frequency is inversely proportional to the bending radius and can be easily controlled by varying it. Neglecting the clamping effects, the resonance frequency is given by:

$$f = \frac{1}{2\pi r}\sqrt{\frac{1}{\rho s_{11}^{E}}} \tag{4}$$

where r is the radius of the curvature and $1/\rho s_{11}^{E}$ and ρ Young's modulus and mass density of curved PVDF film material, respectively. The system includes an operational power amplifier chosen to design a specific electronic circuit capable of driving the PVDF transducer over a wide band around the resonance easy assembled in portable instrumentation or mounting on mobile robots. Because of the ferroelectric polymer's inherent noise, the correct modelling of the transducer's electrical impedance plays an important role in designing the electronic circuits. The actual custom transmitter concentrates all its energy in the frequency band of the transducer. The sonar system makes use of a high performance hemi-cylindrical PVDF transducer working at 60 kHz for the evaluation of the time of flight (TOF) by using the cross correlation algorhythm.

The concentration of VFAs can be measured using spectroscopic or more innovative techniques, such as the electronic nose or biosensors.

The methods of on-line detection of VFAs are divided into three categories: the titrimetic method, the optical method and the sensor/biosensor.

The more reliable methodologies are those which require the use of laboratory instrumentation, such as spectroscopy, which are able to determine the concentration of individual acids besides that of the total concentration.

In the recent years, however, methods that make use of electronic noses have been successfully used experimentally in bioreactors and also in the titration laboratory.

Today, however, the use of biosensors is still in the testing phase. These are based on bacterial and other enzymes which can be used to determine the total concentration of VFAs.

A. The Sensor Agents and the Agency

The outputs resulting by the set of sensors described above in the new protype version should be gathered by the sensor agents that monitors the whole process. It is a complex process, which could be difficult to rule when more anomalies happen at the same time and/or when more biomass units have to be managed.

However, each sensor agent monitors only a biomass cell and when it detects an anomaly then it provides to inform its agency. It, from one hand, monitors and manages the sensor agents and the other component of the system, while from the other hand it has to be interfaced with the agent smart grid. In such a way, the agency should optimize the overall renewable energy processes.

V. Conclusion

This article describes a smart exploitation of biomass for the production of renewable energy in a small rural community in south Italy. The relatively increases the cost of the system aimed at providing energy for short electrical blackout, which can be experienced on the power grid. However, its cost is justified in the situation in which a big plant such as a refrigerator for the storage of vegetables, meat and fish or drugs and other biomedical supplies needs a continuous supply of energy.

The actual system furnishes 10 kW of power for 1 minute. The production of systems capable to deliver electrical power of some kW/h from renewable sources, such as biomass, will be easier and more convenient. From the future adoption of an agent based system to monitor and manage the overall process we hope to take advantage from the consolidate agent technologies. In particular, we hope to overcome the current critical aspects in terms of communication among the different system components and modularity in order to manage in easier way all the changes (e.g., process improvements, new and/or more effective sensors and so on) potentially occurring over time in the renewable energy process.

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