# *Employing Solid Urban Waste in an IIR-SOFC in cogenerative arrangement*

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***Abstract*** **-** In the context of searching for energy and environmentally sustainable systems, fuel cells seem to be an appropriate technology. In particular, those operating at high temperature, possessing the great advantage of flexibility of fuel feeding, can be powered by a gas derived from biological sources. In fact, by treating the organic fraction of solid urban waste in an anaerobic environment, a biofuel, consisting mainly of methane and carbon dioxide, may be produced.

In this paper, the combination of an anaerobic digester with a high temperature solid oxide fuel cell (SOFC) system in a cogenerative arrangement is proposed. The biomass processed involves the provision of biogas feeding the SOFC system. The latter, owing to its high thermal potential, can be arranged with an indirect internal system of fuel conversion into hydrogen that, in contrast to the direct one, reduces the problems of anode carbon deposits.

A technical analysis, to evaluate performances of the integrated system, specifically in relation to the carbon dioxide concentration in the feeding gas, is performed, by using some energy and environmental indexes typical of cogeneration plants.

In this article, in order to test the proposed project, an application to a real case has been made, in which, the biogas plant is designed starting from the organic waste from canteens in the Calabria region. The bio-fuel fed to the SOFC system involves the combined generation of heat and power with which to meet energy needs, estimated by energy audit users.

***Key-Words*** - Organic fraction, Biogas, Anaerobic digestion, Solid Oxide Fuel Cell, Combined Heat and Power, Environmental Impact

## I INTRODUCTION

The fulfillment of the high energy demand [1-2], recorded in recent years, has emphasized the need for environmentally and energy sustainable power systems. On the other hand it has also significantly increased the production of solid waste, causing serious problems for its management in terms of disposal and storage.

The use of municipal solid waste, especially the organic fraction, properly separated by the technique of separate collection, provides an excellent opportunity to generate energy while respecting the environment and rationalizing of resources. In fact, the treatment of "field moist" in an anaerobic environment leads to the production of a quality fuel, consisting primarily of methane and carbon dioxide.

It is in this context that electrochemical fuel cell devices are collocated with great approval, owing to their high energy efficiency with reduced environmental impact generators, in particular, high temperature ones, also have the great advantage of being fed by a variety of fuels.

When these are fed by a derived biological gas the energy system becomes relevant in the context of environmentally sustainable energy production. Biogas is the product of biological processing of waste with no economic value, and compared to other fuels has the great advantage of being renewable and free from NMHC (Non-Methane Hydrocarbons). It is recognized by the United Nations Development Program as one of the most important decentralized energy resources [3].

The technique of anaerobic digestion is widely used for biogas production, whereby the degradation of organic substances takes place in an oxygen-free environment [4].

The product is a high quality gas rich in methane ($CH_4$), and also in carbon dioxide ($CO_2$), often used as feeding gas for energy systems with Internal Combustion Engines and Micro Gas Turbines for CHP applications [5-7].

The great potential derived from municipal waste is clear, in particular from the organic fraction. This can provide a quality fuel to contrast, where and when possible, with "traditional" energy resources (fossil fuels). In this context high temperature fuel cells devices seem to be good competitors for the combined generation of electricity and heat, since this technology seems to be very suitable for energy conversion of biogas.

In this paper an anaerobic digestion plant is combined with a high temperature fuel cell system; the integrated energy system, so arranged, was then studied both from an energetic and an environmental point of view, for the distributed generation of both electrical and thermal energy. The sizing of the biogas plant follows a methodology related to the characteristics of the catchment area of waste in terms of quality and quantity and runs on the basis of the technique chosen from among those in use.

Whereas the selection and evaluation of the fuel cells system is conducted in relation to the characteristics of the input fuel and to the energy performances, power and efficiency, achievable from its feeding.

For the conversion of the primary fuel into a rich hydrogen stream, high temperature electro-chemical devices, thanks to the high thermal potential generated, may be arranged with a reforming system internal to the structure. The referred one is Indirect Internal Steam Reforming (IIR), which unlike the Direct one (DIR), reduces the problem of anode carbon deposits favored by the high temperature.

This occurrence, in the case of biogas powering, could be amplified due to additional parts of carbon from carbon dioxide input. It is generally the cause of electrical efficiency drops, and in order to optimize the system, can be separated from the methane entering the fuel cells system.

Energy and environmental analysis, focused on the determination of some characteristic indexes of cogeneration plants and environmental impact indexes, is an effective tool to make assessments about energy and environmental sustainability of the energy system considered.

An application in the context of the University of Calabria (UNICAL) was made, where, in relation to the daily quantity of organic waste produced by the university canteens, an anaerobic digester was appropriately designed and sized, suitable for the energy conversion of these wastes into biogas. The biogas will be used to feed a system with Solid Oxide Fuel Cells (SOFC), producing electricity and heat in order to meet the energy needs (after an energy audit) of the user considered.

## II DEFINITION AND DIMENSIONING OF AN ANAEROBIC DIGESTION PLANT

Anaerobic digestion is a complex process taking place under conditions of lack of oxygen, with the transformation of organic material into biogas, consisting primarily of methane and carbon dioxide. The quantities of the two main gases vary depending on the type of the treated organic fraction and on the process conditions .

The percentage of methane varies from a 50% minimum to an 80% maximum, the carbon dioxide percentage stands in the range 20-50% and for the rest the remaining part consists of very low percentages of nitrogen ($N_2$), hydrogen ($H_2$), ammonia ($NH_3$) and hydrogen sulfide ($H_2S$) [4].

A variety of different biomasses; pig slurry, cattle slurry, poultry dung, crop residues, non-food crops usually used in combustion systems, organic waste and agro-industry waste water, purified sewage and the organic fraction of municipal waste may be subjected to processes of anaerobic digestion [8-11].

Organic fraction of solid urban waste, if selected by manual collection mechanisms, rather than mechanical selection mechanisms, presents a less quantity of solid materials.

These are inert and strongly contraindicated because they cannot be subjected to any transformations, and so manual selection can provide better yields of biogas.

The anaerobic digestion process can be conducted under high temperature operations, thermophilic conditions (40-60 °C) or under low temperature operations, mesophilic conditions (25-40 °C): the first enables higher yields of biogas, since the process temperature is increased, the decomposition of organic materials is improved by thermophilic bacteria with consequent decrease in the degradation time.

The content of total solids (TS) in organic waste, to be sent to the reactor, determines the possible dilution of the feeding substrate [12]. The presence of the total solids content in percentages about 50% involves the dilution of the substrate with water or with partial recirculation of the effluent by managing the process in a wet mode (wet), but for a content between 25-40% no dilutions is necessary and the process will be managed in a dry mode (dry).

For a proper dimensioning of an anaerobic digestion plant, the correct identification of all the design data is essential, it is very important to identify all those factors characterizing the catchment area: characteristics of the territory, demographic situation, quantity and quality of waste, and state of the collection.

Among the design techniques in use, the most widely used for simplicity is a technique based on the principle of operating parameters, used in this work. The latter is based on some process parameters such as the hydraulic residence average time (HRT), the volumetric organic load (OLR) [12].

Once the amount of daily waste is known, it is necessary to know the chemical and physical properties of incoming materials, including the content in total solids (TS [kg/day]) and in total volatile solids (TVS [kg/day]).

The volumetric organic load and the hydraulic residence average time are linked to a series of prior choices: digestion technique used (wet or dry), method of collection of organic fraction (mechanical or manual selection) and operating conditions (mesophilic or thermophilic). These properties are summarized in Tables I-II.

Table I. OLR values for various processes

| *OLR [$kg_{TVS}/m^3 \cdot day$]* | *Mesophilic* | | *Thermophilic* | |
|---|---|---|---|---|
| | *Wet* | *Dry* | *Wet* | *Dry* |
| *Mechanical selection* | *2.6-4* | *6-9* | *2-5* | *9-15* |
| *Manual selection* | *2-3* | *4-6* | *2-5* | *6-9* |

Table II. HRT values for various processes

| *HRT [days]* | *Mesophilic* | | *Thermophilic* | |
|---|---|---|---|---|
| | *Wet* | *Dry* | *Wet* | *Dry* |
| *Mechanical selection* | *14-30* | *17-30* | *10-18* | *12-20* |
| *Manual selection* | *12-18* | *17-25* | *8-16* | *12-16* |

After the choice of HRT and OLR parameters, the volume of the reactor ($V_R$) can be calculated through (1)

$$V_R = \frac{TVS}{OLR} \quad (1)$$

The resulting reactor volume is responsible for the value of HRT, calculated by using (2),

$$HRT = \frac{V_R}{V_{FS}} \quad (2)$$

The HRT value must belong in the range as above. $V_{FS}$ [$m^3$/day] is the volume of the feeding substrate, calculated by using (3) as the ratio of the organic waste flow rate ($\dot{m}_{OR}$ [kg/s]) to the density of the feeding substrate ($\rho_{FS}$ [$kg/m^3$]).

$$V_{FS} = \frac{\dot{m}_{OR}}{\rho_{FS}} \quad (3)$$

If the value of HRT, given by (2), does not fall into the range reported, it should be performed by successive iterations as shown in Figure 1: the value of OLR has to be varied within the before mentioned range within small spreads then the volume of the reactor recalculated, which is responsible for the recalculated HRT value.

The iteration cycle continues until the verification of the HRT value turns out to be positive.

To reflect the actual final net volume, it is multiplied by a safety factor falling between 1.1-1.3.

For the biogas yield it is necessary to know the daily production of gas calculated as in (4):

$$\dot{m}_B = SGP * TVS \quad (4)$$

where SGP (specific production of biogas [$m^3/kg_{TVS}$]) was calculated by a linear empirical correlation expressed as in (5), in which the coefficients are the result of experimental evidence:

$$SGP = 0.498 - 0.0139 * OLR \quad (5)$$

Then the gas production rate (GPR [$m^3_{biogas}/m^3_{reactor}$]) can be determined as in (6):

$$GPR = \frac{\dot{m}_B}{V_R} \quad (6)$$

Then it is necessary to make some considerations on the quality and therefore on the percentage of the two main gases ($CH_4$, $CO_2$). The biogas, obtained for this type of processed materials, consists essentially of methane, with rates between 60-65%, and carbon dioxide with rates between 30-35%.

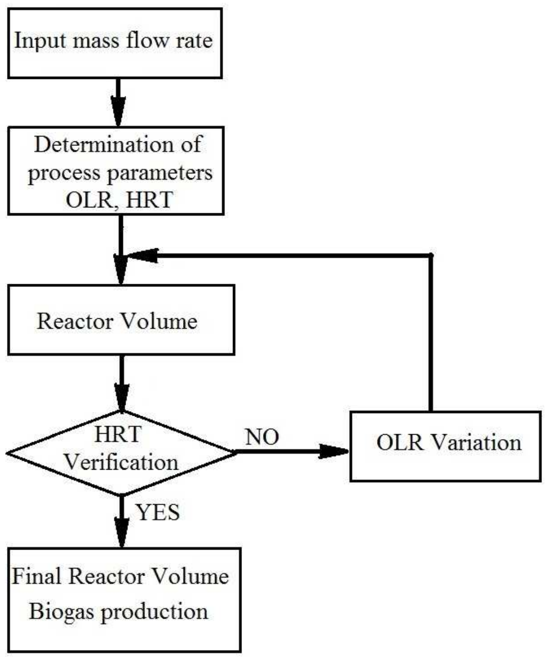


Fig. 1 Flow Chart calculation for reactor dimensioning

Actually the anaerobic digestion plant in its entirety, as shown in Fig. 2, includes a pre-digestion section with the task of receiving and further processing the waste to be fed to the next real section of digestion and a post-digestion section to purify the biogas and to effect the post-treatment of digested sludge with proper storage.

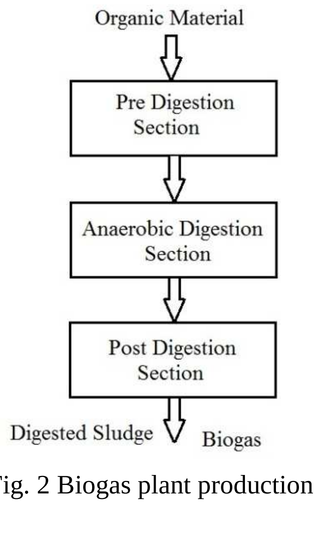


Fig. 2 Biogas plant production

## 3 Choice of fuel cell

Fuel cells are electrochemical systems capable of converting chemical energy of a current "rich"-in hydrogen directly into electricity without the intervention of an intermediate heat cycle, so presenting conversion efficiency higher than those of traditional thermal machines.

Fuel cells show properties that make them promising in the field of energy production (both centralized and distributed form) since they are perfectly consistent with the objectives to pursue in the context of environmentally sustainable energy production:

- high conversion efficiency of primary sources into energy;
- flexibility in the use of fuels, with the possibility of natural gas, syngas, biogas supply, methanol and other liquid fuels. [13-14], after they have been subjected to a reforming process that turns them into hydrogen-rich synthesis gas;
- reduction of emissions of air pollutants;
- low noise;
- possibility of cogeneration.

A complete fuel cell system (Fig. 3) consists of a fuel processing section, including the purification system and reforming system, with the task of producing a hydrogen rich gas stream, of an electrochemical section which is the core of the fuel cell, of a section of power conditioning unit with the task of achieving the delivery of an alternating current in agreement with the request voltage, and of a heat recovery section. Everything is "governed" by a control system.

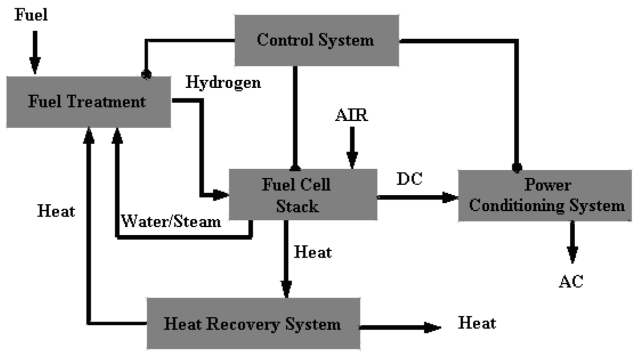


Fig. 3 Fuel cell system block diagram

Plants with fuel cells, thanks to their modularity, flexibility, efficiency and environmental compatibility can be applied both to small loads (from a few kW to some MW), and to large utilities (some MW to tens of MW). There are different types of fuel cells that are classified on the basis of type of electrolyte used that determines the operating temperature range, connoting low operating temperature devices (50-200 ° C) and high temperature devices (600 - 110 ° C).

One type of fuel cell, at the moment the most representative, of those at low temperature operation is the polymer electrolyte fuel cell (PEMFC) [15-16], while the devices at high temperature operation are molten carbonate fuel cell (MCFC) and solid oxide fuel cells (SOFC).

Although low temperature fuel cells have several advantages that make them acquire the role of preferential competitors in the field of distributed micro-generation, on the other hand, the very low thermal regime causes a number of disadvantages relative to the quality of the gas stream produced in the reforming section to be sent to the feeding section.

Low operating temperature causes problems of a technological nature associated with the need of using

catalysts based on noble metals such as platinum, which would be poisoned if the gas stream did not contain certain requirements, namely high purity hydrogen. Extremely low concentrations of CO (a few ppm), would be fatal for the good working of the fuel cells.
Advantages are relatively low start-up times and fast response to load variations that make the electrochemical device very suitable for residential installations with possible in-house locations.

High temperature fuel cells, despite the disadvantages that the high temperature operations have namely strength of materials decay, closely related to the useful life of the device, higher start-up times and high response time to load variations, have all the gains from the high operating temperature in addition they show higher electrical efficiency (45-50%) than low temperature fuel cells (40 % maximum).

The high quality potential heat is available both for domestic and industrial heating, with the possibility of creating CHP (Combined Heat and Power) [17-18] systems, and also for the realization of a downstream energy cycle by introducing gas and/or steam turbines (hybrid systems): receiving the upstream waste energy of the electrochemical device, electrical efficiency would be increased by several percentage points ($\eta$=55-65%) [19-21].

Whereas low-temperature fuel cells have the strict need to be fed with a stream rich in hydrogen with purity approaching 100%, high temperature fuel cell are not affected by this limit. High temperature involves reforming internal to the structure to benefit the available potential heat directly, and means that the chemical reactions involved are favored without using expensive catalysts.

The possible presence of chemical substances different from hydrogen in the feeding stream gas that did not completely undergo the process of transformation to hydrogen, would be consumed partly in the electrochemical reactions.

Since in the present work an integrated energy system in CHP arrangement is proposed to produce electricity and heat by using as fuel, the biogas produced by the anaerobic digestion of organic waste, it therefore appears sensible, for the reasons set out above, to aim attention towards the adoption of a system of power generation with high temperature fuel cells. In particular SOFC systems (Solid Oxide Fuel Cell) work well in cogeneration arrangements thanks to their electrical and thermal vocation. SOFCs are also taken into account by research and industry for their predisposition to be powered by "alternative" fuel such as biogas.

In this work, therefore the energy system chosen for energy conversion of the biogas efficiency is SOFC.

## 4 Biogas treatment section

The systems, universally recognized for producing a hydrogen-rich gas from a "primary" fuel, refer to the technology of reforming [22].

It is a highly endothermic process and so it needs large amounts of heat to set it up.

The transformation can be accomplished by a process of Autothermal reforming, in which the supply of thermal energy comes from a partial combustion of the converting gas, and by a process of Steam reforming, in which the heat required is provided from "outside".
Steam Reforming, so named for the active role played by the water, is usually adopted.

In a gas conversion into a hydrogen-rich gas, the reactions involved are: the reforming reaction as explained as in (7) and the Water Gas Shift reaction (WGS) explained as in (8).

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \tag{7}$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \tag{8}$$

The promoter of the process is the water molecule, which in the first reaction is given the task of tearing the hydrogen atoms from methane thus producing hydrogen and carbon monoxide, and in the second, it has the task of converting carbon monoxide to $CO_2$ producing additional hydrogen.

In fuel cell sectors, generally classified as low and high temperature fuel cells, the high temperature ones have the peculiarity of being powered by a hydrogen-rich gas stream - and not necessarily only by hydrogen - as in the case of those operating at low temperature. In addition, among other positive characteristics, they produce thermal energy, part of which can be used for the reforming section. This section, in many configurations of these types of fuel cells is internal to them and in this case the process is called Internal Reforming. In particular, adopting the "Indirect" technology (Indirect Internal Reforming, IIR) rather than Direct (Direct Internal Reforming DIR), whereby the reformer is internal to the electrochemical section but physically separate from the anode, it reduces the problem of carbon deposits on the anode compartment.

This problem is particularly felt in the case of biogas feeding where $CO_2$, precisely because of its division, causes the formation of Carbon. It should just be noted that from a point view of the electrochemical reaction, however, the presence of $CO_2$, in addition to the aforementioned carbon deposition problem, is an obstacle to the meeting of hydrogen molecules with oxygen anions. All this causes a fall in efficiency.

Moreover, in the section of an usual steam reformer presenting a Steam to Carbon (S/C) ratio of about 2, the $CO_2$ content, found in the input fuel, is the cause of a shift in the equilibrium of the Water Gas Shift (WGS) reaction towards larger production of reagents, transforming, in fact, a WGS into RWGS (Reverse Water Gas Shift) (9) implying the opposite effect to that desired [23-24]. The negative effect that occurs is that the hydrogen produced by the first reforming reaction is consumed in favor of water and carbon monoxide. The effect, in part, is then canceled because the carbon monoxide in turn becomes fuel for the electrochemical stage in which it would be consumed [25]

$$CO_2 + H_2 \leftrightarrow H_2O + CO \tag{9}$$

It just should be noted that, on the other hand, $CO_2$ can be considered as a reforming promoter, by exerting an active role in the process. In the technical literature it is much suggested the idea of exploiting entirely also the amount of $CO_2$ present in the biogas revising the reforming system. In this case the reforming turns into a Dry Reforming using "dry gases" as promoters of the process.

In (10), the Dry $CO_2$ Reforming is expressed.

$$CH_4 + CO_2 \leftrightarrow 2H_2 + 2CO \quad (10)$$

Although in the present paper this type of process has not been taken into account, which the authors would like to develop in future projects, it is useful to clarify that in the case of biogas powering, this possibility can be contemplated.

A Dry $CO_2$ reforming to may be run, a $CO_2/CH_4$ ratio about 10 is required [26].

A typical biogas presents a $CO_2/CH_4$ ratio of about 0.6: much lower than that required. In these conditions carbon deposit problems could arise. Since this ratio is too low, the carbon dioxide alone cannot fulfill the task of providing the fuel conversion, additional substances must to be involved to complete the process.

$H_2O$ or $O_2$ should be used. For simplicity of system, the choice tends towards air [27] setting up a Dry $O_2$-$CO_2$ reforming. On the other hand, it was noted that with the introduction of $H_2O$, thus realizing the combination of a Steam reforming with a Dry $CO_2$ Steam reforming, the benefits obtained are very satisfactory [24].

In this paper an usual Indirect Internal Steam Reforming, widely tested and used, is taken into account.

## 5 ENERGETIC-ENVIRONMENTAL ANALYSIS

An energetic-environmental analysis enables assessments about the performances of the integrated system. Assessments in terms of energy performances were made through the calculation of the electrical and thermal production, accompanied by the calculation of some indexes characterizing the energy cogeneration plants. An environmental analysis, through the calculation of a specific environmental impact indicator, was performed to assess the level of pollution emissions.

Electricity and heat were calculated by using (11-12),

$$E_{el} = \dot{m} \cdot \eta_{el,SI} \cdot LHV \quad (11)$$

$$E_{th} = \dot{m} \cdot \eta_{th,SI} \cdot LHV \quad (12)$$

where $\dot{m}$, expressed in [$m^3$/year], is the gas flow rate, $\eta_{el\text{-}SI}$ e $\eta_{th\text{-}SI}$, are the electrical and thermal efficiencies for the global integrated system, and LHV is the lower calorific value. To obtain this value the methane lower calorific value is taken as reference and it is equal to 10.36 [$kWh/Nm^3$] in standard condition (STC).

Fuel consumption, expressed as in (13), was referred to the required electricity,

$$C_F = \frac{E_{el}}{\eta_{el,SI} \cdot LHV} \quad (13)$$

The characteristic energy indexes considered in this work [28, 29] are given below.

The first-law efficiency highlights the useful result, then the production of electricity and thermal energy in reference to the theoretically extractable energy from the primary fuel. It is defined by using (14)

$$\eta_{tot} = \frac{E_{el} + E_{th}}{\dot{m} \cdot LHV} = \eta_{el} + \eta_{th} \quad (14)$$

The equivalent efficiency, expressed as in (15), adds two terms of a different nature converting the $P_{th}$ term into precious energy (mechanical work or electricity)

$$\eta_{eq} = \eta_{el} + \frac{\eta_{el} \cdot \eta_{th}}{\eta_{th}^*} \quad (15)$$

The conversion of fuel into power factor $F_{FP}$, expressed by using (16), is an electrical efficiency and it is defined as that term that assigns the remaining fuel rate to the electrical generation after removing the consumption of a hypothetical conventional boiler that generates the thermal power $P_{th}$ of the CHP system separately.

$$F_{FP} = \frac{\eta_{el}}{1 - \dfrac{\eta_{th}}{\eta_{th}^*}} \quad (16)$$

The primary energy saving index $I_{PES}$, (17), is a very useful formulation to identify the quality of CHP, it involves the potential fuel savings achieved by a CHP system compared to the separate generation of the same amount of electrical energy and heat.

$$I_{PES} = 1 - \frac{1}{\dfrac{\eta_{el}}{p \cdot \eta_{el}^*} + \dfrac{\eta_{th}}{\eta_{th}^*}} \quad (17)$$

The terms marked with (*) refer to the values of $\eta_{el}$, $\eta_{th}$ of reference as suggested by the AEEG (Autorità per l'Energia Elettrica e il Gas) Directive (Conditions for the approval of combined heat and electricity cogeneration as defined in Article 2, paragraph 8 of Legislative Decree 16 March 1999 No 79 Decision No 42/02). This directive suggests choosing a value of 0.38 for the average electrical efficiency of plants that generate only electricity and a value of 0.8 for the thermal efficiency of thermal power generation plants for civil use.The term *p* is a coefficient representing the electrical transmission losses avoided since the cogenerative system uses its own electricity production.

It is calculated by using (18)

$$p = \frac{p_{IN} \cdot E_{el,IN} + p_{cons} \cdot E_{el,cons}}{E_{el,IN} + E_{el,cons}} \quad (18)$$

where the *"IN and cons"* terms represent respectively the outgoing amounts, injected into the electrical transmission, and the amounts consumed by the user.

In case of connection to the middle voltage line, terms $p_{IN}$ and $p_{cons}$ have a value about 1-2.8/100 e 1.43/100.

The $I_{PES}$ index, since the plant is approved by the European Union (EU) as a cogenerative system, must reach a value of 10 %.

In the assessment of environmental sustainability an index of environmental impact $I_{ENV}$ is involved [29]. It refers to the potential impact on air pollution produced by emissions of the main greenhouse gases typically emitted from a thermal power plant: $CO_2$, CO, SOx, NOx, and VOC. Each of these gases is directly or indirectly responsible for various phenomena related to climate change, there is no uniquely accepted way to determine the overall impact that pollutants have on the environment. Each chemical component can contribute to more environmental effects, and to a different extent depending on the considered effect.

The Environmental Impact Index is based on a system of equivalence factors which allows the consideration , on the basis of limit values established by law, of the various pollutants from an emitting source. This can be done on the basis of a reference measurement unit, the kg of equivalent $CO_2$, used to determine the overall environment impact by the source. Table III summarizes the limit values of the considered emissive substances and their conversion factors. It can be seen as CO, SOx, NOx and VOCs (Volatile Organic Compounds) have high conversion factors, which produce significant negative impacts on the environment in relation to $CO_2$; anyhow these compounds are produced in small amounts compared to carbon dioxide.

The environmental impact indicator, given in (19), will be calculated as the pondered sum in $kgCO_{2eq}$./kWh of used fuel:

$$I_{Env} = \sum_i p_i * S_i \qquad (19)$$

$S_i$ is the pollutant, measured in kg/kWh of fuel, and $p_i$ is the conversion factor, expressed as $kg_{CO2eq}$/kg. The index can be expressed in kWh of the produced electricity as reported as in (20):

$$I_{Env,el} = \frac{\sum_i p_i * S_i}{\eta_{el}} \qquad (20)$$

Table III Emissions, emissions limits and conversion factors for various pollutants

| | *SOFC* | *ICE* | *MGT* | | |
|---|---|---|---|---|---|
| *Si* | *[kg/kWh$_{fuel}$]* | | | *Limits* | *$p_i$* |
| | | | | *[kg/year]* | *[kg $_{CO2}$eq/kg]* |
| *$CO_2$* | 186 | 180 | 180 | *$100·10^6$* | *1* |
| *CO* | 0.008 | 0.87 | 0.16 | *$500·10^3$* | *200* |
| *$SO_X$* | 0 | 0 | 0 | *$150·10^3$* | *1000* |
| *$NO_X$* | 0.01 | 0.87 | 0.14 | *$100·10^3$* | *666.67* |
| *VOC* | 0.002 | 0 | 0 | *$100·10^3$* | *1000* |

## 6 A REAL APPLICATION CASE

In the present work the use of an integrated system anaerobic-digester fuel cell was proposed in the context of the University of Calabria (UNICAL).

The University of Calabria is a university with about 40000 people considering students, faculty staff, consumers, consisting of residential structures, offices, commercial premises, premises used for catering (canteens) and spaces for educational use (classrooms, laboratories, etc.). Its architecture consisting of 90 cube-shaped buildings is very unusual. The latter are structures with a regular geometric cube shape, the average size is 21 m ·21 m ·21 m.

The integrated energy system will provide for the processing of large amounts of organic waste already separated by the method of manual separate collection, from canteens, into biogas and then, after prior treatment, will be sent to the downstream fuel cell for the production of electricity and heat that will satisfy the needs of some buildings in the same university.

### A. Input and output data of the production of biogas

Starting from 11900 kg of waste per day, an estimate made by the competent authority, the anaerobic digester properly dimensioned in the manner expressed in a previous paragraph.

The catchment area, to which calculations are referred, is represented by the structures of food service in the University of Calabria. This simplified the analysis of data collection since there was no need to analyze the territory and demography characteristics, because the related area has a limited extension.

The system of catering waste collection, within these environments, is already present and is a manual separate collection type with separation in glass, plastics and organic materials.

About the material quality, values of total solids and total volatile solids were chosen to be equal to 25.6 [%] for TS and equal to 96.5 [% TS] for TVS [12]. For the feeding substrate, $\rho_{FS}$, a value about 350 kg/m$^3$ has been assessed.

For the sizing of the reactor, given the nature of organic waste, a technique of dry digestion was considered, and a system operating in thermophilic condition was adopted, to be managed at temperature $T_R$ equal to 55 °C and pressure $P_R$ equal to 1 bar. The biogas that is reached (1940 m$^3$ per day), has a percentage of $CH_4$ equal to 64%.

The input, output and process data of the plant are summarized in Table IV.

Table IV Anaerobic digester input, process and output data

| *Input* | |
|---|---|
| *$\dot{m}_{OR}$ [kg/day]* | *11900* |
| *$\rho_{FS}$ [kg/m$^3$]* | *350* |
| *TS [%]* | *25.6* |
| *TVS [% TS]* | *96.5* |
| *Process* | |
| *$T_R$ [°C]* | *55* |
| *$P_R$ [bar]* | *1* |
| *$V_R$ [m$^3$]* | *511.27* |
| *Output* | |
| *$\dot{m}_b$ [m$^3$/day]* | *1940.25* |
| *GSP [m$^3$/kgTVS]* | *0.66* |
| *GPR [m$^3_{biogas}$/m$^3_{reactor}$*day]* | *3.80* |
| *$CH_4$ in biogas [%]* | *64* |
| *Biogas Power (LHV) [kW]* | *536* |

### B. Selection and evaluation of SOFC

In the field of high temperature fuel cells, the SOFC typology could be a very appropriate technology for the energy conversion of biogas achieving reasonably high electrical efficiency (30-40%) already at low power (5-20 kW) and at high concentrations of carbon dioxide present in the fuel supply [27, 30].

In addition to presenting the advantages of high temperature operations, among other important advantages are: high electrical and thermal efficiencies, flexibility to be powered by different fuels, internal self-sustenance of reforming, SOFCs have additional benefits compared to other high temperature devices.

For example, since all the components are in the solid state, problems of corrosion and evaporation, typical of cells with liquid electrolyte, are eliminated, and also SOFCs have the flexibility of geometric shapes.

There are two geometric configurations of solid oxide fuel cells, planar and tubular. Planar geometry is not very present and it is not very developed because of a series of construction problems, including the fragility of components and the difficulty in achieving effective sealing. On the contrary, tubular geometry has now achieved good reliability [31] and it is the cell configuration most commonly used. Its peculiarity comes from the fact that seals are not present.

Among various cell technologies, tubular SOFC, thanks to both the operating temperature and the used materials, has the potential to be competitive in the distributed energy field.

By contrast, however, there are also disadvantages related to the degradation of materials and their assemblage, also, due to the high thermal inertia involved, transients appear to be quite long resulting in long start-up times and responses to load changes.

The reference generator is SW CHP PC 100 type ($P_{el}$=110 kW, $\eta_{el}$=47 %, $\eta_{tot}$=80%) [32]. This is a tubular solid oxide fuel cell with indirect internal steam reforming. A demonstration plant of this kind is operating at the GTT (Gas Turbine Technology) in Turin [33] which achieved 29000 hours in May 2006 and completed 40000 working hours in 2007 [34]. This duration is taken as objective by solid oxide fuel cell manufacturers by virtue of an imminent penetration of the energy system in the market in order possibly to compete with more mature technologies.

In biogas, as mentioned above, together with $CH_4$ there is also a significant percentage of $CO_2$, which does not cause only carbon deposits, as already announced, but it results in the reduction of the hydrogen stream and also inhibits the electrochemical reaction to which hydrogen is subjected, causing efficiency loss. Nevertheless, by modeling activities [35] it resulted that tubular IIR-SOFC with steam reforming also at carbon dioxide high contents present low efficiencies drops. Fig. 4 shows that for a biogas with $CO_2$ content which may even reach 40% , the electrical efficiency decreases to a 35% level.

As mentioned in relation to the disadvantages, it is not convenient to use the SOFC in intermittent operations in relation to periods of increased energy needs, but it should be considered for work phases in continuous cycle and at nominal power levels.

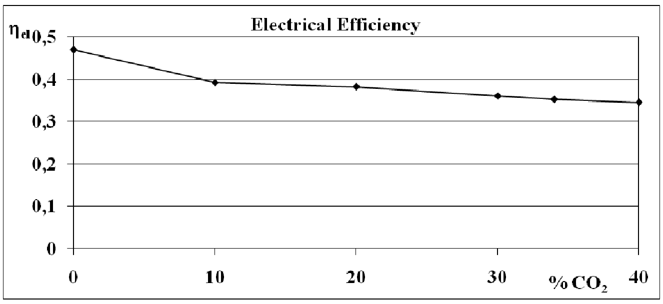


Fig. 4 Tubular IIR-SOFC electrical efficiency vs % $CO_2$ content in biogas

*C. Energy audit of the users*

In order to determine the electrical and thermal needs of locals and in order to satisfy them with the integrated system, it was necessary to carry out an investigation at the UNICAL Energy Manager offices. The data refer to electrical and thermal energy consumptions of the cubes, for the year 2007, respectively, equal to $16.7 \cdot 10^6$ [kWh/year] and $15 \cdot 10^6$ [kWh/year].

From this data, with reference to the dynamics of consumption for typical structures of this kind, an elaboration of the possible electrical and thermal load patterns was made. The regulations imposed by the 01/09/1991 Law for heat consumption must be taken into account: the urban area of Cosenza, in which UNICAL is located, is bound to the use of heating from 11/15 to 03/31 for a total of 10 hours per day from 9.00 am at 7:00 p.m. Figs 5-7 show the dynamics of loads per all cubes, per cube, and per volume, over the year. 300 days of activities are taken into account, excluding completely the months of August and December, and part of January and April because, during these periods, the canteen activities are not active for holidays and celebrations. In addition, it was also suggested, in an unlikely manner, that academic activities being completely suspended for the same reasons given above, even the universities facilities cancel their energy consumption.

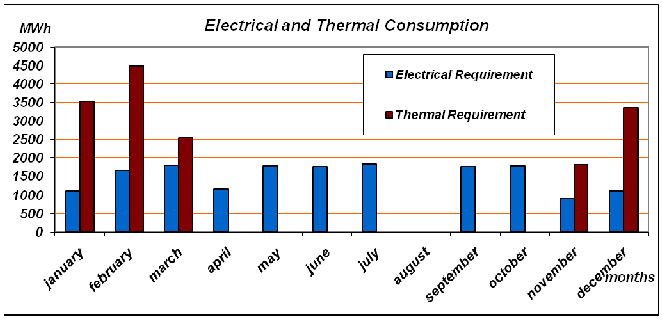


Fig. 5 Energy Consumption for 90 cubes

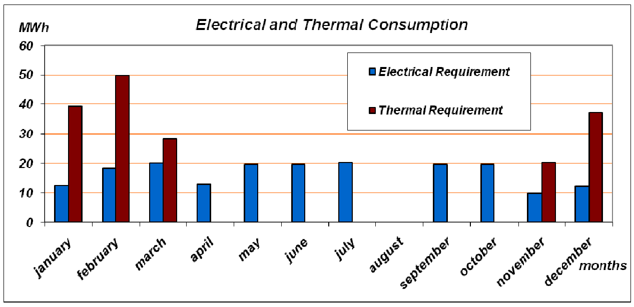


Fig. 6 Energy Consumption per cube

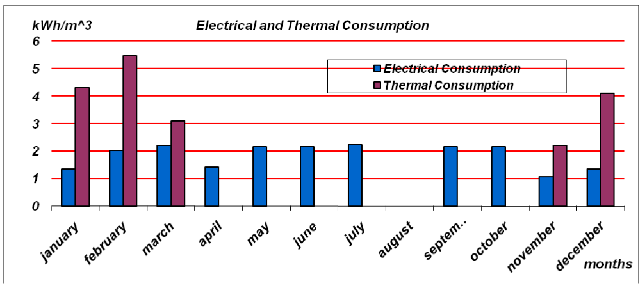


Fig. 7 Energy Consumption per volume unit

Referring to the diagram in Fig. 6, it shows that the energy consumption is never lower than 13 MWh, it is a threshold value obtained in a seasonal transition month such as is the month of April. The graphic presents the maximum value, about 20 MWh, in summer months, during which the electrical consumption is increased by the reversible heat pumps work. The minimum heat consumption is recorded in November, about 20 MWh, and reaches a maximum in February, about 41 MWh, when heating is needed at full capacity.

*D. Analysis of results*

In the data processing for the biogas plant was taken into account an absorption of electric and thermal energy respectively equal to 15% and 35%. These quantities are required to perform the main functions of the plant, mainly for mechanical devices work and heaters. Taking into account only of the $CH_4$ content, the fuel flow rate supply of the fuel cells, in this case two SOFC, SW CHP PC 100, was found to be about 52 $m^3$ / h.

The integrated system, in Fig. 8 is basically composed of a system of biogas anaerobic digester, a possible system for the separation of $CO_2$ and two solid oxide fuel cell devices.

Since by experimental data [33] it was shown that feeding one SOFC, of the same kind used in this work, with 26 kg/h of natural gas, the latter produces 125 kW of electrical power in alternating current. This data was taken as reference for the nominal electrical power in the case of biogas supply with a negligible $CO_2$ content.

Analyzing the values in Table V, it appears that, at lower $CO_2$ concentrations, the system responds with the best energy performance. In particular, it has to be noted that a boundary value for the $CO_2$ content is the value of 20% as the electrical power system, diminished by the internal absorption of the entire equipment, is equal to a 174 kW and $I_{PES}$ index appears to be close to the value of threshold so that a system is recognized as CHP.

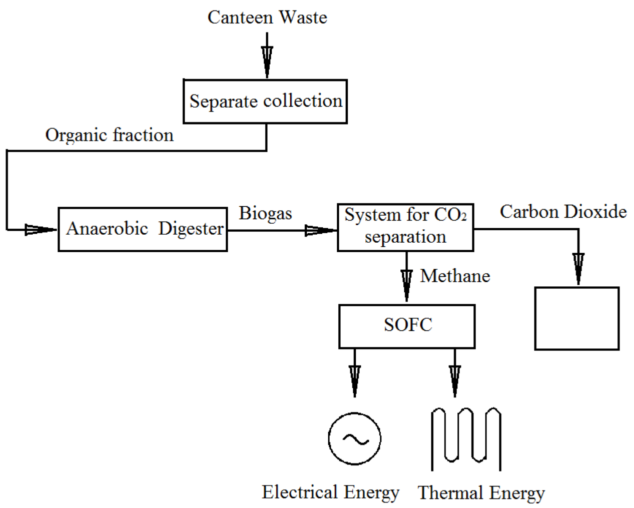


Fig. 8 Integrated System block diagram

From an energy point of view the electrical efficiency was made to vary with the percentage of $CO_2$ present in the biogas, as described above, while the thermal efficiency was kept fixed at the nominal fuel cell rate diminished by quantity related to the internal thermal absorption.

Regarding other energy indexes, they assume the growth trend expected versus the decreasing of the $CO_2$.
From energy production data, comparing them with the energy needs of the users, it was found that 8 cubes can be powered electrically on a yearly basis and just one cube can be served by heat.

The results of the environmental review showed that the integrated system appears to be an example and model of an environmentally friendly plant, because each pollutant and climate-altering factor is well below the limits imposed by the regulations.

Table V Integrated system performances at different values of $CO_2$ content in biogas

| *% $CO_2$* | *40* | *36* | *30* | *20* | *10* | *~0* |
|---|---|---|---|---|---|---|
| *SOFCs electrical performances* | | | | | | |
| *$\eta_{el}$ %* | *34.5* | *35.2* | *36* | *38.2* | *39.2* | *47* |
| *$P_{el}$ kW* | *185* | *188* | *193* | *205* | *210* | *250* |
| *Integrated system electrical performances* | | | | | | |
| *$P_{el}$ kW* | *157* | *160* | *164* | *174* | *178* | *212* |
| *$\eta_{el}$ %* | *29.3* | *30* | *31* | *32.5* | *33.3* | *40* |
| *Integrated system thermal performances* | | | | | | |
| *$P_{th}$ kW* | *115* | | | | | |
| *$\eta_{th}$ %* | *21.45* | | | | | |
| *$\eta_{tot}$ %* | *50.8* | *51.4* | *52.1* | *53.9* | *54.8* | *61.4* |
| *$F_{FP}$ %* | *40.07* | *40.88* | *41.81* | *44.37* | *45.53* | *54.59* |
| *$\eta_{eq}$ %* | *29.96* | *30.56* | *31.25* | *33.14* | *34.00* | *40.72* |
| *$I_{PES}$ %* | *4* | *5* | *7* | *11* | *13* | *24* |

A comparison of this integrated system was then performed with more mature energy systems in the context of cogeneration, i.e. internal combustion engines ICE and micro gas turbines MGT. The comparison was conducted considering the fuel supply after a possible process of $CO_2$ abatement, for example using polymer membrane separation [23]. The ICE and the MGT were taken into account, which are of sizes ranging 100-200 kW for electrical power. In this range an efficiency of 32% is representative for the ICE and 29% for the MGT and thermal efficiency of 53% is representative for the ICE and 52% for the MGT [36]. The results of the comparison are shown in Table VI. Fig. 9 summarizes the energy productions. The electrical efficiency and electrical equivalent efficiency are higher for the SOFC, meaning that a better use of primary energy source was achieved. The $F_{CP}$ index indicates approximately same values for SOFC and ICE, the $I_{PES}$ is higher for SOFC, meaning that these systems have a higher CHP value.

Table VI Comparison between ICE, MGT, SOFC

| | *ICE* | *MGT* | *SOFC* |
|---|---|---|---|
| *$\eta_{el}$ % (*)* | *32* | *29* | *47* |
| *$\eta_{el}$ %* | *27.2* | *24.65* | *40* |
| *$\eta_{th}$ % (*)* | *53* | *52* | *33* |
| *$\eta_{th}$ %* | *34.45* | *34* | *21.45* |
| *$\eta_{tot}$ %* | *62* | *58* | *61* |
| *$\eta_{eq}$ %* | *44* | *41* | *50* |
| *$F_{FP}$* | *47.8* | *42.7* | *54.7* |
| *$I_{PES}$* | *12.8* | *6.6* | *24.3* |
| *$P_{el}$ [kW]* | *146* | *132* | *212* |
| *$P_{th}$ [kW]* | *185* | *182* | *115* |

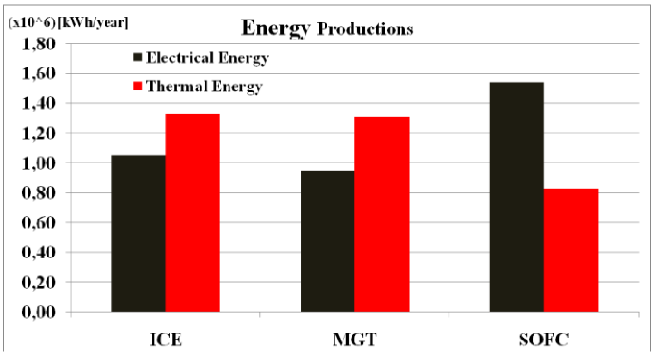


Fig. 9 Systems Energy Production

As for the service delivered to users, the integrated system with ICE and MGT compared to the SOFC, serve heat for a greater number of cubes (3 blocks) thanks to their higher thermal efficiency, but electrically fewer (6 blocks for ICE, and 5 blocks for MGT) due to their lower efficiency. Figs. 10-11, respectively, highlight the annual dynamics of the structure served monthly and yearly by the three energy systems: it is clear that the system integrated with SOFC is always greater from respectively the electrical point of view, but not so in terms of heat.

The fuel consumption as determined on the basis of the electricity required from a single cube, turns out to be much higher for ICE (66000 $m^3$/year) and MGT (73000 $m^3$/year) compared to the SOFC system (45000 m3/year) (Fig. 12).

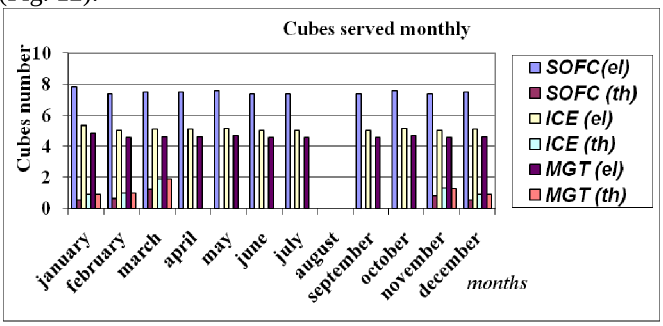


Fig. 10 Number of cubes monthly served

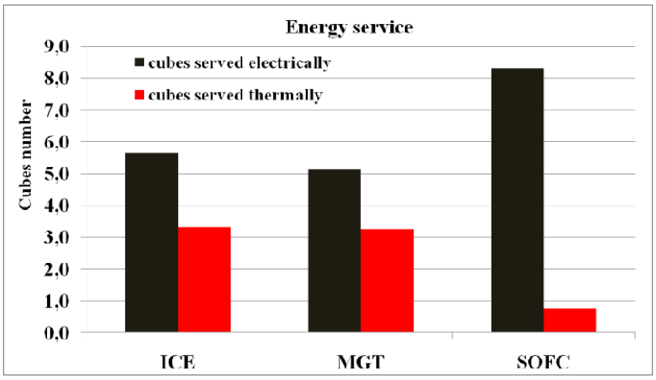


Fig. 11 Number of cubes yearly served

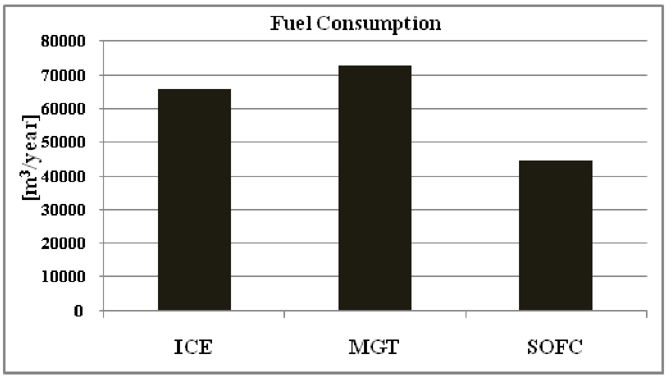


Fig.12 Fuel Consumption by serving one cube

Table VII shows the results of the comparison on the basis of the environmental analysis .

Table VII Values of $I_{env}$, $I_{env,el}$ and annual emissions for different energy systems

| | *MGT* | | *ICE* | | *SOFC* | |
|---|---|---|---|---|---|---|
| | $I_{-env}$ | *Emissions* | $I_{-env}$ | *Emissions* | $I_{-env}$ | *Emissions* |
| | $kg_{CO2eq}$ | *kg/year* | $kg_{CO2eq}$ | *kg/year* | $kg_{CO2eq}$ | *tonn/year* |
| $CO_2$ | 1864.8 | $13.5 \cdot 10^6$ | 1864.8 | $13.4 \cdot 10^6$ | 1927 | $13.9 \cdot 10^6$ |
| *CO* | 339.808 | $12.2 \cdot 10^3$ | 1806.8 | $65 \cdot 10^3$ | 16.6 | $0.6 \cdot 10^3$ |
| $SO_X$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $NO_X$ | 1408.96 | $10.1 \cdot 10^3$ | 9034 | $65 \cdot 10^3$ | 103.6 | $0.7 \cdot 10^3$ |
| *VOC* | 0 | 0 | 0 | 0 | 20.7 | $0.15 \cdot 10^3$ |
| *TOT* | $3.6 \cdot 10^3$ | $13.5 \cdot 10^6$ | $12.7 \cdot 10^3$ | $13.5 \cdot 10^6$ | $2.1 \cdot 10^3$ | $13. \cdot 10^6$ |
| $I_{-env,.el}$ | $15.7 \cdot 10^4$ | | $4.7 \cdot 10^4$ | | $5.2 \cdot 10^3$ | |

The system which uses solid oxide fuel cell has lower values of environmental impact indexes, obviously, all three respect the emission limits.

## 7 Conclusions

In the present paper the possibility of studying an integrated anaerobic digester-Solid Oxide Fuel Cell system, for a more rational use of the energy sources, was investigated.

The design of the anaerobic digestion plant and the determination of the quantity and quality of biogas produced through it were carried out by considering the techniques of thermophilic process under dry condition.

A high temperature solid oxide fuel cells system, with tubular geometry and indirect internal steam reforming, given the high electrical efficiency and the quality of the thermal energy produced, was used. The flexibility of this, to be powered by different fuels, enabled the feeding of biogas consisting of methane and carbon dioxide. The latter, owing to its percentage in the biogas, however, does not preclude the proper operation of the fuel cell.

For the evaluation of the CHP system, a technical analysis was performed, focusing the calculations on the determination of some energetic and environmental indexes, efficiency, energy production, other characteristic indexes for cogeneration plants and an environmental impact indicator.

To test and verify the integrated plant an application was made. By employing the solid urban waste derived from the canteens of the University of Calabria, 11900 kg of organic material were extracted by the technique of separate collection. This amount of waste used in a properly designed anaerobic digester, led to a production of about 1940 $m^3$/day of biogas, with which to feed the 220 kW SOFCs system.

An energy audit, in order to establish the number of cube-shaped buildings to serve electrically and thermally, was performed.

The comparison of the proposed plant with many more systems used in the cogeneration field, thanks to the present very well-established reliability and good performances, like Internal Combustion Engines and Gas Turbines, pointed out that the integrated system has the best features of CHP structures. It is also the one that has less fuel consumption.

An environmental sustainability as well as an energy sustainability is verified by calculations. Emission values much lower than regulatory limits and environmental impact indexes lower than the widely marketed modern and advanced energy systems emerged. The system involves the disposal of zero economic value material in order to estimate a high energy value "product".

Systems of this kind contribute actively to the reduction in effective volume of landfills (sites approved for the accumulation and storage of municipal solid waste). In addition the adoption of fuel cells compared to the traditional systems involves the reduction of pollutant emissions for a better quality of air, generating clean energy aiming for environmental and energetic sustainability.

Future developments will focus on the study of alternative reforming, which include, in the processes associated with it, the use of the $CO_2$ content in biogas and the possibility of exploiting the high thermal potential of the integrated system for trigeneration targets.

SIMBOLOGY

| | |
|---|---|
| $V_R$ | Reactor Volume [$m^3$] |
| $V_{FS}$ | Feeding Substrate Volume [$m^3$] |
| TVS | Total Volatile Solidi [kg/day] |
| OLR | Organic Volumetric Load [kgTVS/$m^3$*day] |
| $m_{OR}$ | (Daily) Organic Residuals Rate [kg/day] |
| $\rho_{FS}$ | Feeding substrate density [kg/$m^3$] |
| $T_R$ | Reactor Temperature [°C] |
| $P_R$ | Reactor Pressure [bar] |
| GSP | Biogas Specific Production [$m^3$/$kg_{TVS}$] |
| GPR | Biogas Production Rate [$m^3_{Biogas}/m^3_{Reactor}$] |
| HRT | Hydraulic Residence average Time [days] |
| $\dot{m}_B$ | Biogas Rate [$m^3$/days] |
| $E_{el}$ | Electrical Energy [kWh], [MWh] |
| $Et_h$ | Thermal Energy [kWh], [MWh] |
| $P_{el}$ | Electrical Power [kW] |
| $P_{th}$ | Thermal Power [kW] |
| $R_{th/el}$ | Thermal-Electrical Ratio |
| $\dot{m}$ | Fuel Rate [$m^3$/year] |
| $C_F$ | Fuel Consumption [$m^3$/year] |
| $\eta_{el}$ | Electrical Efficiency |
| $\eta_{th}$ | Thermal Efficiency |
| $\eta_{el,SI}$ | Electrical Efficiency of the Integrated System |
| $\eta_{th,SI}$ | Thermal Efficiency of the Integrated System |
| LHV | Low Heat Value [kWh/$m^3$] |
| $\eta_{tot}$ | Total Efficiency |
| $\eta_{eq}$ | Equivalent Efficiency |
| $F_{FP}$ | Fuel to Power conversion Factor |
| $I_{PES}$ | Primary Energy Saving Index |
| p | Coefficient of reduced electrical transmission losses |
| $p_{IN}$ | Coefficient of reduced electrical transmission losses referred to the amount of electricity injected into the transmission line |
| $p_{cons}$ | Coefficient of reduced electrical transmission losses referred to the amount of electricity self consumed by the user |
| $E_{el,IN}$ | amount of electrical Energy injected into the transmission line |
| $Eel,_{cons}$ | amount of electrical Energy self consumed by the user |
| $I_{Env}$ | Environmental impact Index [$tonn_{CO2}$] |
| $I_{Env,el}$ | Environmental, electrical impact Index [$tonn_{CO2}$] |
| Pi | Conversion pollutants to $CO_2$ Factor [$tonn_{CO2eq}$/tonn] |
| Si | Pollutant Emission [kg/$kWh_{fuel}$] |
| $CO_2$ | Carbon Dioxide |
| CO | Carbon Monoxide |
| $SO_x$ | Sulphur Oxides |
| $NO_x$ | Nitrogen Oxides |
| VOC | Volatile Organic Compounds |

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