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OPTIMIZATION OF BIOENERGY SOLUTIONS AT DIFFERENT FARM SCALES

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ABSTRACT

RAF is a bio-energetic descriptive model integrates with MAD model to support Integrated Farm Management. RAF model aimed to enhancing economical, social and environmental sustainability of farm production in terms of energy via convert energy crops and animal manure to biogas and digestate (bio-fertilizers) by anaerobic digestion technologies, growing and breeding practices. The user defines farm structure in terms of present crops, livestock and market prices and RAF model investigates the possibilities of establish on-farm biogas system (different anaerobic digestion technologies proposed for different scales of farms in terms of energy requirements) according to budget and sustainability constraints to reduce the dependence on fossil fuels. The objective function of RAF (Z) is optimizing the total net income of farm (maximizing income and minimizing costs) for whole period which is considered by the analysis.

The main results of this study refers to the possibility of enhancing the exploitation of the available Italian potentials of biogas production from on-farm production of energy crops and livestock manure feedstock by using the developed mathematical model RAF integrates with MAD to presents reliable reconcile between farm size, farm structure and on-farm biogas systems technologies applied to support selection, applying and operating of appropriate biogas technology at any farm under Italian conditions.

Also the main results indicates to the flexibility and ability of RAF model to offers reliable Key design elements (preliminary design) of on-farm biogas production system, and it is worth to mention that, accurate description, calculation and optimization of this Key design elements are the crucial factor to selection, applying and operating of appropriate biogas technology at any farm under Italian conditions.

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ACRONYMS

Technical terms	Description
AD	Anaerobic digestion
BTTP	Block type thermal power
CSTR	Completely stirred tank reactor
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
C / N	Carbon to nitrogen ratio
CHP	Combined heat and power
DM	Dry matter
e.g.	Exempli gratia “for example”
FF	Fresh feedstock
GHG	Greenhouse gases
GUI	Graphical use interface
HRT	Hydraulic retention time
LSU	Livestock unit
MSW	Municipal solid waste
Mtoe	Million tons of oil equivalent
NH_3	Ammonia
ORC	Organic Rankine cycle
PINGE	Pilot injection natural gas engine
ppm	Parts per million
SRT	Solids retention time
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

Conversion units

KiloWatt (kW)	= 1000 Watts
MegaWatt (MW)	= 1000 kW
GigaWatt (GW)	= 1 million kW
TeraWatt (TW)	= 1 thousand million kW
1 Joule (J)	= 1 Watt second = 278 x 10^{-6} Wh
1Wh	= 3600 J
1 cal	= 4.18 J
1 British Thermal Unit (BTU)	= 1055 J
1 cubic meter (m^3)	= 1000 liter (L)
1 bar	= 100000 Pascal (Pa)
1 millibar	= 100 Pa
1 psi	= 6894.76 Pa
1 torr	= 133.32 Pa
1 millimeter mercury (0°C)	= 133.32 Pa
1 hectopascal (hPa)	= 100 Pa

DISCLAIMER

For clear distinguish between technical terms "Mass and Volume" of the same materials used as feedstock for biogas production per unit of time, the author used the technical term "Volume" for express the inner-volume of different components of on-farm biogas system, while used the technical term "Quantity" for express the volume of feedstock and substrates used for biogas production per unit of time.

1

INTRODUCTION

1. INTRODUCTION

1.1. Biogas is a promising energy carrier

Biogas is a non-conventional, promising renewable energy carrier, which combines the disposal of organic waste with the formation of a valuable energy carrier, methane. On the other hand biogas energy characterized as the best way of derive energy from polluted wastes, clean, eco-friendly, money saver, time saver, and minimizes expenditure of the foreign currency for the import of fossil fuels.

Currently, accumulation of organic wastes considers one of the most environmental problems in our society. In most industrial countries, they are applying sustainable waste management; moreover the one of the major political priorities is reduction accumulation of organic wastes, which leads to Intensify efforts of reduce pollution, Greenhouse Gas emissions (GHG) and to mitigate global climate changes. The aim of sustainable waste management is produce energy, recycling of nutrients and organic matter Instead of uncontrolled waste dumping, which no longer acceptable today (**Kossmann *et al.*, 1999 and Al Seadi *et al.*, 2008**).

One of the most important and modern technologies, which dealing with recycling of organic wastes is Anaerobic Digestion (AD) of digestible organic waste (agricultural by-products and wastes, animal manure and slurries), which converts these substrates to renewable energy carrier (biogas), reduce the GHG, produce an excellent natural fertilizer for agriculture purposes and achievement many social and economic benefits for the producer and consumer of biogas (**Dennis and Burke, 2001**).

AD is a microbiological process of anaerobic decomposition (in the absence of oxygen) of the organic matter, which produces biogas in air-proof reactor tanks, commonly named digesters. Biogas produced in many natural environments and widely applied today. There is a wide range of micro-organisms are decomposition the organic matter in anaerobic process, which has two main end products: biogas and digestate. Biogas is a combustible gas; mainly it is a mix of methane, carbon dioxide and small amounts of other gases and trace elements. Digestate is the decomposed substrate, which rich in nutrients and suitable to be used as plant fertilizer (**Kossmann *et al.*, 1999; Kramer, 2004 and Al Seadi *et al.*, 2008**).

The first production of biogas was in UK in 1895. Since then, the biogas production process was developed and applied widely for wastewater treatment and sludge stabilization. The energy crisis in the mid of 70s of twenty century has been created a new dimensions of biogas production and use. Currently, the interesting of biogas is grow up, due to international efforts for partially replacing of the fossil fuels by renewable energy because its benefits such as realized environmentally sustainability, recycling of agricultural by-products and residues, animal manure and other organic wastes (**Kossmann *et al.*, 1999; Dennis and Burke, 2001 and Al Seadi *et al.*, 2008**).

Today, In Asia alone (especially in China, India, Nepal and Vietnam), millions of families uses small-scale digesters to produce biogas for multi purposes (such as cooking and lighting). Multi thousands of agricultural biogas plants have been established in Europe and North America, many of them using the latest technologies within this area, and their number is continuously growing (**Kossmann *et al.*, 1999; Dennis and Burke, 2001 and Al Seadi *et al.*, 2008**).

1.2. Comparative advantages and disadvantages of biogas

Biogas production and use has multi environmental and socioeconomic benefits for domestic and commercial use.

1.2.1. Comparative advantages

1.2.1.1. Socioeconomic and environmental benefits

1. One of the main sources of renewable energy:

   Production process of biogas from biomass is permanently renewable (unlike fossil fuels), where solar energy storage during photosynthesis in biomass and biomass converts during AD to biogas, which improves the energy balance of the state and also make an positive contribution for protection the natural resources and environment (**Al Seadi *et al.*, 2008 and European Biomass Association, 2009**).

2. Participation in reduction of greenhouse gas emissions and mitigation of global warming:

   Combustion of fossil fuels (such as coal, crude oil and natural gas) releases emissions of carbon dioxide (CO_2 is one of the most important GHG) into the atmosphere, which causes global warming. The combustion of biogas also releases CO_2, but the main difference between biogas and fossil fuels is that, the carbon in biogas was recently absorbed from the atmosphere during photosynthetic process of plants, so that the carbon cycle of biogas is thus closed within a very short time (between one and several years), while carbon cycle of fossil fuels closed within a very long time(between thousands and millions years), so that using of biogas helps to reduce global warming (**European Biomass Association, 2009 and Esfandiari and Khosrokhavar, 2011**).

3. Reduced quantities and risk of imported fossil fuels:

   The countries, which do not have high reserves of fossil fuels depending on import large quantities of fossil fuels, which concentrated in few geographical areas of our planet. Import of fossil fuels is risky, such as transport for long-distance, leakage of oil or gas and volatility of prices, which creates a permanent insecure status due to dependency on import of energy. Most European countries are strongly dependent on fossil energy imports from regions rich in fossil fuel sources such as Russia and the Middle East. Most of European countries have great potentials to produce biogas from AD, depending on national and regional biomass resources, which will increase security of national energy supply and reduce dependency on imported expensive fuels (**Kossmann *et al.*, 1999 and Al Seadi *et al.*, 2008**).

4. Organic wastes are valuable resource of renewable energy:

   European countries produce large quantities of organic wastes from industry, agriculture and households and convert this organic wastes to biogas presents an excellent way for energy production, followed by recycling of the digested substrate as fertilizers. AD can also contribute to reducing the volume of waste and of costs for waste disposal (**Kossmann *et al.*, 1999; Al Seadi *et al.*, 2008 and European Biomass Association, 2009**).

5. Creation of jobs:

   Biogas production from AD consists of many processes such as collection and transport of AD feedstock, manufacture of technical equipment, construction, operation and maintenance of biogas plants, all this process depending on trained labors. From the other hand development of a national biogas sector lead to the establishment of new enterprises, which increases the income in rural areas and creates new jobs (**Kossmann *et al.*, 1999; Kramer, 2004 and European Biomass Association, 2009**).

6. Biogas is flexible and versatile:

   Biogas is flexible energy and suitable for multi uses such as direct use for cooking and lighting, but in many countries biogas is used nowadays for combined heat and power generation (CHP) or it is upgraded and fed into natural gas grids, used as vehicle fuel or in fuel cells (**Kossmann *et al.*, 1999; Kramer, 2004; Al Seadi *et al.*, 2008 and European Biomass Association, 2009**).

7. Minimum water requirements:

   AD process requires the lowest amount of water for processing when compared with other biofuels. This is an important aspect related to the expected future water scarcity in many regions of the world (**Kramer, 2004 and European Biomass Association, 2009**).

1.2.1.2. Benefits for the producers

1. Additional source of income for farmers:

   Biogas production technologies are economically and attractive for farmers and provides them additional income. The farmers get also a new and important social role as energy suppliers and waste treatment operators (**Al Seadi *et al.*, 2008 and European Biomass Association, 2009**).

2. Digestate is an excellent fertilizer:

After production of biogas, the by-product of AD is digested, which consider a valuable soil fertilizer, rich in nitrogen, phosphorus, potassium and micronutrients, and can be applied on soils with the usual equipment for application of manure. Compared with raw animal manure or compost, digestate has improved fertilizer efficiency due to higher homogeneity and nutrient availability, better C / N ratio and significantly reduced pathogenesis and odors (**Kramer, 2004 and Lukehurst *et al.*, 2010**).

3. Closed nutrient cycle of biogas:

The biogas production from AD provides a closed nutrient and carbon cycle from the production of feedstock to use of digestate as fertilizers (Fig. 1.1). When the methane (CH_4) is combustion the carbon dioxide (CO_2) is released to the atmosphere and retaken by vegetation during photosynthesis. Some carbon compounds still remains in the digestate, which increase the carbon content of soils, when digestate is use as fertilizer (**Kossmann *et al.*, 1999; Al Seadi *et al.*, 2001; Al Seadi *et al.*, 2008 and Lukehurst *et al.*, 2010**).

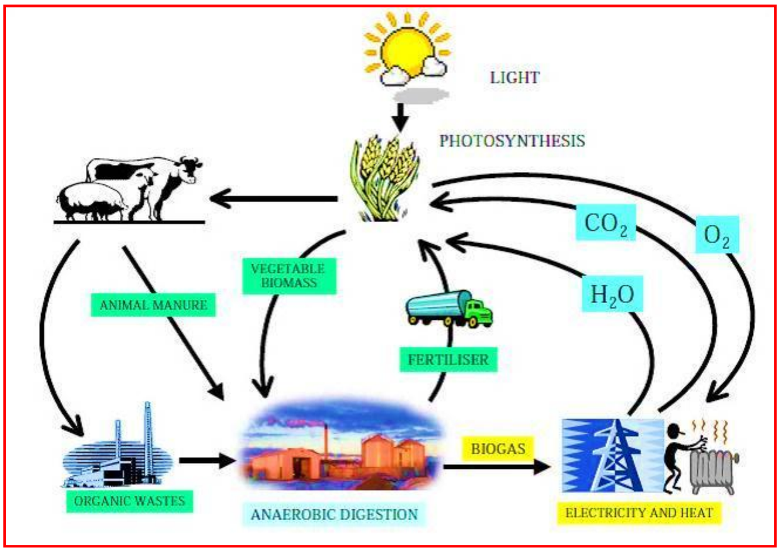

Fig. 1.1: The sustainable cycle of biogas from AD (as *cited in* **Al Seadi *et al.*, 2001**)

4. Biogas produces from multi feedstocks:

   Biogas could be produced from multi feedstocks such as wet biomass, which has moisture content more than 60 % (*e.g.* sewage sludge, animal slurries, flotation sludge from food processing etc.). Currently, many of energy crops (grains, maize, rapeseed), have been widely used as feedstock for biogas production in countries like Austria, Germany and Italy. Besides energy crops, all kinds of agricultural by-products and wastes, damaged crops, unsuitable for food or resulting from unfavorable growing and weather conditions, can be used to produce biogas and fertilizer (**Kossmann *et al.*, 1999; Kramer, 2004 and Lukehurst *et al.*, 2010**).

5. Disposal of odors and insects:

   Animal dung and many organic wastes are sources of unpleasant odors and attract insects, but AD reduces these odors by up to 80 % (**Kossmann *et al.*, 1999; Al Seadi *et al.*, 2008 and Lukehurst *et al.*, 2010**).

6. Improve Veterinary safety:

   Use a digestate as fertilizer improves veterinary safety compared with application of untreated manure and slurries. In general, the aim of sanitation is to inactivate pathogens, weed seeds and other biological hazards and to prevent disease transmission by use AD process of organic waste by save way (**Kossmann *et al.*, 1999; Al Seadi *et al.*, 2008 and Lukehurst *et al.*, 2010**).

1.2.2. Comparative disadvantages

According to **Huisman *et al.* (2007); Grieg-Gran *et al*. (2009) and Bond and Templeton (2011)** there are a few disadvantages of biogas:

- The process of digestion reduces the total solids content in the feedstock (energy crops, by-products and manure yield) and thus there is a volume loss of the organic waste compared to composting, however both can produce a fertilizer;
- Biogas contains contaminant gases which can be corrosive to gas engines and boilers;
- Digestate must meet high standards in order to be used on land without detrimental effect on agricultural uses especially with food crops;

- Biogas plants and gas upgrading plants both have a relatively high heat and energy requirements, which required some of the biogas yield to be used on-site;
- Will only produce a limited quantity of energy demand and is dependent upon location in proximity to feedstock and energy users;
- There is little or no control on the rate of gas production, although the gas can, to some extent be stored and used as required;
- Small- and middle-scale of anaerobic technologies for the treatment of solid waste in middle- and low-income countries is still relatively new;
- Experts are required for the design and construction, depending on the scale of biogas plant and may also for operating and maintenance;
- Reuse of produced energy (*e.g.* transformation into, fire / light, heat and power) needs to be established;
- High sensitivity of methanogenic bacteria to a large number of chemical compounds and fluctuation of temperature and steering during the digestion process;
- Unwanted odor can be emitted from sulphurous compounds.

1.3. Current situation and potentials of biogas production in Italy

Currently, the use of biomass for energy purposes contributes for just 3.5 % to the final national energy consumption (180.2 Mtoe[1]) but with a production equal to about 6.2 Mtoe, bioenergy represent 29.5 % of the whole amount of energy from renewable sources in Italy (21,1 Mtoe). The biogas contribution to the total bioenergy production is about 8 % (8.4 % of the electricity production from biomass sources, Fig. 1.2) (**ENEA, 2010**).

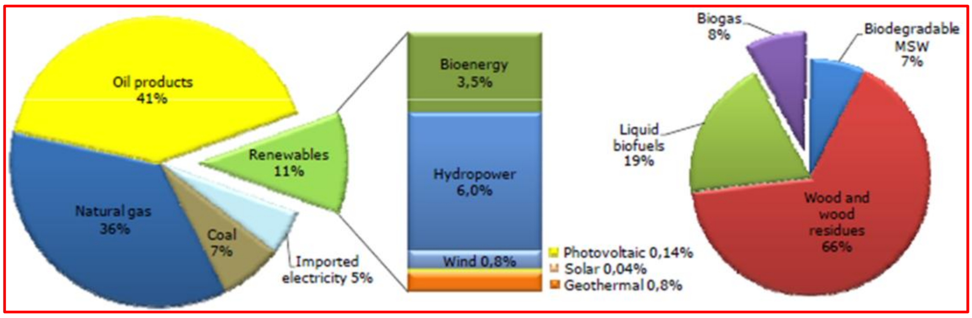

Fig. 1.2: Energy use by source and bioenergy contribution in Italy in 2009 (as *cited in* **ENEA, 2010**)

[1] Million tons of oil equivalent

Regional distribution of Italian biogas sector shows that, biogas plants are mainly located in the northern regions and more than 60 % are related with the agriculture and zoo-technical sector as illustrated in Fig. (1.3). 50 % of agriculture and zoo-technical biogas plants use co-digestion mixture of energy crops, by-products, residues and animal manure.

Fig. 1.3: Number and distribution of biogas plants by feedstock until 31 December 2010 (as *cited in* **CRPA, 2011**)

According to **ENEA (2010)** could summarize the current state of biogas in Italy as follow:

- Biogas production in 2009 was about 0. 499 Mtoe;
- 78 % of biogas production coms from MSW[2] Landfills (228 plants);
- 451 plants feed by a mixture of different substrates (from agroindustry, agro-zoo-technical residues and sewage sludge);
- The total installed capacity is about 507.7 MW (including landfills);
- A recent growing trend of biogas sector comes from the growing of the agro-industrial and zoo-technical biogas production.

[2] Municipal solid waste

1.3.1. National target of nREAP for bioenergy until 2020

The National Renewable Energy Action Plan (nREAP) sets for bioenergy in Italy a target by 2020 equal to 9.82 Mtoe (0.834 Mtoe of biogas), in order to cover 19 % of electricity, 54 % of heating and cooling and 87 % of transport fuel of the total consumption from renewable energy sources (**ENEA, 2010**).

The capacity of renewable energy produced in 2009 (6.238 Mtoe, including 0. 499 Mtoe from biogas) equal to 63.5 % compared to the target set for 2020 by the nREAP (9.82 Mtoe). Such a target could seem ambitious, but is considerably smaller than the estimated potentials (24 - 30 Mtoe / year, see Table 1.1) for bioenergy in Italy, able to cover up to 13 - 17 % of the total energy demand (**ITABIA, 2009 and ENEA, 2010**).

Table 1.1: Italian potentials of bioenergy (author elaboration *cited in* **ITABIA, 2009**)

Biomass	**Mtoe / year**
Residues from agricultural and agro-industrial	5
Residues from forestry and wood industry	4.3
Municipal solid waste	0.3
Livestock manure	10 - 12
Firewood	2 - 4
Energy crop	3 - 5
Total	**24 - 30**

1.3.2. Italian potentials of biogas production

If we sum all quantities of energy crops (over set-aside lands) plus agricultural residues, livestock manure, agroindustry residues, MSW and sewage sludge, we could roughly estimate a potential of about 65 million m^3 / year of feedstock available for biogas production (**CRPA, 2011**).

A total of 1.3 million m^3 of biogas / day can be produced only from livestock manure that could result in a total biomethane production of 237 million m^3 / year which is about 10 times more than the actual needs of methane used for transports in Italy (**CRPA, 2011**).

1.4. Mathematical modeling and optimization of anaerobic digestion

Mathematical models are describing anaerobic digestion systems by using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, or game theoretic models. These and other types of models can overlap, with a given model involving a variety of abstract structures. In general, mathematical models may include logical models, as far as logic is taken as a part of mathematics. In many cases, the quality of a scientific field depends on how well the mathematical models developed on the theoretical side agree with results of repeatable experiments. Lack of agreement between theoretical mathematical models and experimental measurements often leads to important advances as better theories are developed. There are two types of anaerobic digestion mathematical models:

- Descriptive models;
- Controlling models.

Optimization is finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones. In comparison, maximization means trying to attain the highest or maximum result or outcome without regard to cost or expense. Practice of optimization is restricted by the lack of full information, and the lack of time to evaluate what information is available. In computer simulation (mathematical modeling) of biogas systems, optimization is achieved usually by using linear programming techniques of operations research.

Batstone *et al.* (2002) mention that structured model includes multiple steps describing biochemical as well as physic-chemical processes. The biochemical steps include disintegration from homogeneous particulates to carbohydrates, proteins and lipids; extracellular hydrolysis of these particulate substrates to sugars, amino acids, and long chain fatty acids (LCFA), respectively; acidogenesis from sugars and amino acids to volatile fatty acids (VFAs) and hydrogen; acetogenesis of LCFA and VFAs to acetate; and separate methanogenesis steps from acetate and hydrogen / CO_2. The physic-chemical equations describe ion association and dissociation, and gas-liquid transfer. Implemented as a differential and algebraic equation (DAE) set, there are 26 dynamic state concentration variables, and 8 implicit algebraic variables per reactor vessel or element. Implemented as differential equations (DE) only, there are 32 dynamic concentration state variables.

Lindmark (2005) implemented a Biogasopt-project, aimed to improve the biogas process by focusing on some key issues in the process, namely pretreatment of the incoming substrate, mixing inside the digester and membrane filtration of the process water. The Process can be split up into three different parts (pretreatment, digestion and sludge treatment) which can be improved and optimized independently of each other but still leads to an overall efficiency increase of the process.

Fiorese *et al.* (2008) proposed a method to evaluate the AD plants convenience on a given territory by an economic, energy and emissive point of view. A mathematical model is formulated in order to optimize biomass use by finding the optimal AD plants' number, capacity, location, and the corresponding biomass collection basin. The method is applied to the district of Cremona, one of the most important Italian farming areas. The optimal solution is achieved by widespread AD plants over the territory in order to exploit biomass locally. Biomass transportation is minimized for its high costs are not balanced by economies of scale. AD plants in Cremona yield positive returns in economic terms, as energy produced and GHG emissions avoided (7 % reduction with respect to 2003). The robustness of this result has been confirmed by sensitivity analysis of the plant and transportation costs. The final result is crucial for local planning of biomass exploitation: local governments can encourage the development of conversion plants at municipal level without the need for centralized decisions.

Aworanti *et al.* (2011) developed a mathematical model for the prediction of the behavior of microbial processes. The development of the models was based upon a material balance analysis of the digester operation, substrate utilization, cell growth and product formation. The model was solved using Runge kutta numerical technique embedded in polymath software. The digesters' operations simulated with a starting valve of 300 g / dm^3 as the concentration of the substrate and 1.5 g / dm^3 as the concentration of the cell, within a period of 13 days. The results of the simulation show that the substrate concentration shows exponential decline from (300 g / dm^3 to 6.88 g / dm^3), the cells growth shows exponential trend from (1.5 g / dm^3 to 39 g / dm^3) The rate of growth of cell was increased from (0.5 g / dm^3 - 2.53 g / dm^3), death increased from (0.015 g / dm^3 to 0.161 g / dm^3) over the 13 days and the biogas production which is the product also follow the exponential trend from (zero concentration to 219 g / dm^3). In all the model does the prediction well on all the parameters simulated, so it was can be used to predict the product formation rate as well as the design of reactor or digester.

Dewil *et al.* (2011) mention that although anaerobic digestion is a widely applied technology, the process is not yet fully understood because of its high complexity and an optimization of the current technology is still needed. The design and control of digester systems is still generally performed by rule-of-thumb since no tools are currently available for an accurate evaluation of performance. The application of mathematical models is a prerequisite to improve digester performance and hence much attention is focused on the development of accurate models.

Budhijanto *et al.* (2012) developed a mathematical model based on a simplified mechanism of anaerobic digestion for analyze the digestion phenomena quantitatively and objectively in order to make quick decisions in the optimization of the installed digesters in the field. The data from field measurements were used to fit the mathematical model for predicting the rate of biogas production and the selectivity of methane production over carbon dioxide formation. Simulation using the model led to more systematic field trials to improve the digester performance. The analysis resulted in two useful hints for the practical improvement of the digesters. Firstly, the selectivity of methane over carbon dioxide was significantly affected by the ratio of water and manure in the slurry. Secondly, the conversion of the organic matters into biogas could be increased by recycling a portion of the digester effluent.

Normak *et al.* (2012) were used IWA Anaerobic Digestion Model No.1 (ADM1) to simulate the anaerobic digestion process of cattle slurry. The model was applied to 200 l single stage completely stirred tank reactor. The simulation results of pH, biogas flow rate, acetate and methane concentration were under study. Ammonia inhibition constant was optimized during this study to improve modeling results compared to measurements of acetate concentration. Maximum methane yield during experiment was 291 l / kg VS_{added} at organic loading rate 2.0 kg VS / m^3 . day.

Subramani and Nallathamb (2012) developed a pilot scale model of 20 liters capacity to evaluate the maximum yield of biogas from domestic sewage and kitchen waste. The organic loading and hydraulic retention time of 25 days studied to improve the production of biogas. A computer program developed for optimum allocation of the above factors to generate more biogas based on the feedstock effluent samples characteristics, such as pH, total solids, volatile solids, volatile fatty acid contents, number of days and alkalinity. A various digestion options and operational factors analyzed to make the commercial production of biogas. The study aimed to use biogas instead of coal and petroleum which are non-renewable resources and fast depleting.

Vindiš *et al.* (2012) developed a system for multi-criteria evaluation of energy crops for biogas production. First, a deterministic simulation system consisting of deterministic production simulation models was built. Simulation model results were further evaluated using a qualitative multi-attribute modeling methodology DEX (supported by the software tool DEX-i). Analysis showed that by using the current model the most relevant alternative crop for biogas production is maize. Maize results in the best DEX-i multicriteria evaluation appropriate. The best alternatives for maize are sorghum, sunflower, and sugar beet, with multicriteria evaluation being less appropriate.

1.5. Objective of the study

Due to continued rapid growth of the Italian biogas sector during the last years and for improving the exploitation of the Italian potentials of biogas production from on-farm production of energy crops and livestock manure feedstock to meet the growing demand of energy, there is a need to address the following problems:

- Farm size (different farm scales) and farm structure (on-farm crops and livestock distribution and production) suitable for establish on-farm biogas system to cover the on-farm thermal and electrical energy requirements;

- Selection of appropriate technology from different available technologies of anaerobic digestion, biogas production and use, for applying at different farm scales with different farm structures.

As previously mentioned there are many mathematical models processing the different biogas problems and improving the biogas production, but there is a need to develop a mathematical model to reconcile between farm size, farm structure and on-farm biogas systems technologies applied to support selection and applying of appropriate biogas production technology at any farm under Italian conditions.

The objective of this study is enhancing the exploitation of the available Italian potentials of biogas production from on-farm production of energy crops and livestock manure feedstock by develop a mathematical model (RAF) integrates with (MAD[3]) model already has been developed for optimize the following on-farm variables, related to anaerobic digestion and biogas production and use (Fig. 1.4):

- Allocated surface areas, distribution and production of different on-farm crops under different farm sizes (scales) (optimum data of MAD);
- Number of on-farm LSU[4] (from different available types of farm livestock) (optimum data of MAD);
- Key design elements[5] of on-farm biogas production system (directs and helps to select the suitable technologies of on-farm biogas system) (optimum data of RAF);
- On-farm labor requirements (optimum data of RAF and MAD);
- The total net income of farm (optimum data of RAF and MAD).

[3] MAD is a bio-economical model aimed to optimize resources of a farm holding (surfaces, livestock, labor, etc.) to approach an objective function aimed to maximize net income.
[4] Livestock unit
[5] Some references refer to key design elements as "design criteria"

1.5.1. Description of RAF model

The outlines of RAF model could be summarized as following (Fig. 1.4):

1. RAF is a bio-energetic descriptive model in terms of sets of equations (or inequalities) run by uses GAMS code and GUI (Graphical Use Interface) works under MATLAB environment for optimize the objective function (Z) (optimization the total net income of farm for whole period which is considered by analysis);
2. RAF model support Integrated Farm Management (IFM) by enhancing economical, social and environmental sustainability of farm production;
3. RAF model supports decision maker, engineers and farmers;
4. RAF model investigates the possibilities of establish on-farm biogas system (different anaerobic digestion (AD) technologies proposed for different scales of farms in terms of energy requirements) for reduce the dependency on fossil fuels and recycling the agricultural and animal by-products for produce energy and digestate (bio-fertilizers);
5. The output data of optimization process presents a preliminary design of on-farm biogas production system which contains the key design elements (*e.g.* dimensions, quantities, capacities of main components of on-farm biogas production system);
6. The output data of optimization process could be presented in form of recommendations for the best investment in energy from different on-farm potentials under different farm sizes (scales).

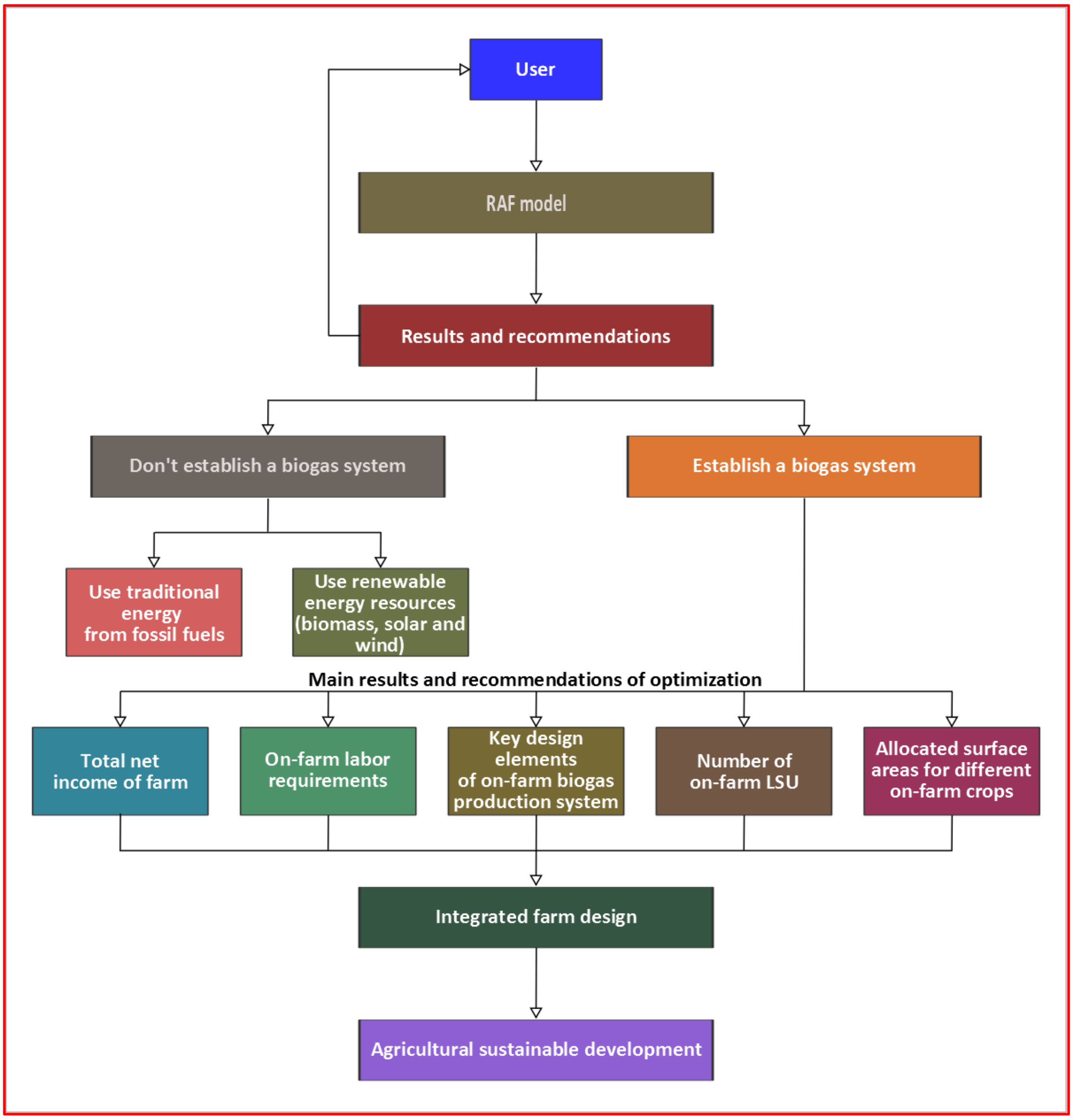

Fig. 1.4: The outlines of RAF model, main results and recommendations of optimization process

2
REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

2.1. Anaerobic digestion (AD)

The biochemical conversion technologies depending on obtain energy from chemical reactions by the action of enzymes, fungi and micro-organisms, which are decomposition biomass under specific conditions for producing bioenergy carriers such as biogas and ethanol. The biochemical conversion technologies are fit for use with the biomass contains values of C / N ratio less than 30 and moisture content more than 30 % on the basis of dry-mass (**Lampinen, 2005**).

Two such processes are widely used, and have been used for millennia: anaerobic digestion (acid fermentation) and alcohol fermentation. Their conversion technologies for energy products are illustrated in Fig. (2.1).

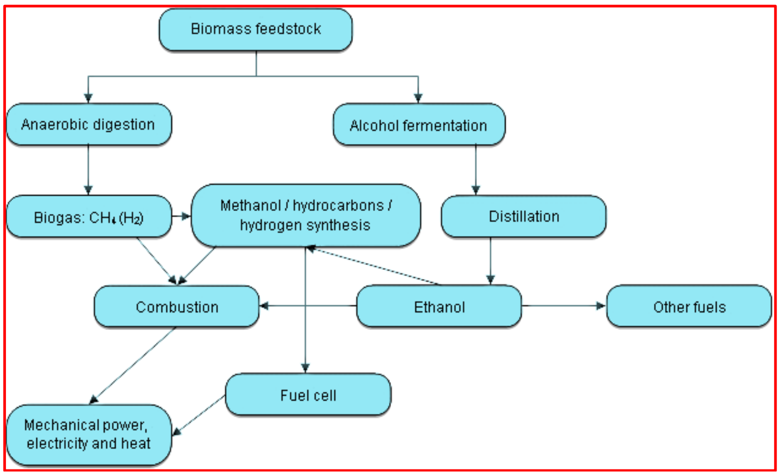

Fig. 2.1: Biochemical conversion technologies for anaerobic digestion and alcohol fermentation (author elaboration *cited in* **Lampinen, 2005**)

In the field of renewable energy, an anaerobic digestion refers to bio-chemical conversion technology, designed for convert organic matter to energy. Biogas is a kind of gas that is produced during the anaerobic processing of organic matter such as energy crops and by-products, manure or even municipal waste materials. Biogas typically consists mainly of methane, with a significant proportion of carbon dioxide, and smaller quantities of other gases such as nitrogen and hydrogen (**Kramer, 2004; Lampinen, 2005 and European Biomass Association, 2009**).

AD is a biochemical decomposition process of organic matter in absence of oxygen, by various types of anaerobic microorganisms. The outputs of AD process are the biogas and the digestate. When the substrate of AD is consists of mixture from two or more feedstock types (*e.g.* energy crops and by-products, animal slurries and organic wastes from food industries), the process is called "co-digestion" and it is common in most biogas applications currently (**Kossmann *et al.*, 1999; Kramer, 2004; Lampinen, 2005 and Al Seadi *et al.*, 2008**).

2.1.1. Biomass types and characteristics related to AD

Many types of organic matters can be used as substrates (feedstock) for biogas production from AD. According to **Bio Fuel Cells Concepts for Local Energy (2000); Dennis and Burke (2001); Al Seadi *et al.* (2008) and European Biomass Association (2009)** the most common biomass types used in European biogas production are listed below and tabulated in Table (2.1):

- Energy crops (*e.g.* maize, sorghum, miscanthus, clover and etc.), agricultural by-products and wastes;
- Animal by-products and wastes;
- Digestible organic wastes from food and agro-industries (vegetable and animal origin);
- Organic fraction of municipal waste and from catering (vegetable and animal origin);
- Sewage sludge.

Using animal manure and slurries as feedstocks for AD process have some advantages according to their characteristics:

- Contain a naturally content of anaerobic bacteria;
- Contain high moisture content (4 – 12 % dry matter in slurries on the basis of wet-mass), which acting as solvent for the other substrates and improve mixing and flowing of mixture;
- Available in cheap price;
- Easy to collect and use from animal farms.

Table 2.1: Bio-wastes suitable for biological treatment (author elaboration *cited in* **Al Seadi *et al.*, 2008 and European Waste Catalogue, 2009**)

Waste Code	Waste description	Waste sources
02 00 00[6]	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing
		Wastes from the preparation and processing of meat, fish and other foods of animal origin
		Wastes from the fruit, vegetables, cereals, edible oils, cocoa, tea and tobacco preparation and processing: conserve production; yeast and yeast extract production, molasses preparation and fermentation
		Wastes from sugar processing
		Wastes from the dairy products industry
		Wastes from the baking and confectionery industry
		Wastes from the production of alcoholic and non-alcoholic beverages (except coffee, tea and cocoa)
03 00 00	Wastes form wood processing and the production of panels and furniture, pulp, paper and cardboard	Wastes from wood processing and the production of panels and furniture
		Wastes from pulp, paper and cardboard production and processing
04 00 00	Wastes from the leather, fur and textile industries	Wastes from the leather and fur industry
		Wastes from the textile industry
15 00 00	Wastes packing; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified	Packaging (including separately collected municipal packaging waste)
19 00 00	Wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use	Wastes from anaerobic treatment of waste
		Wastes from waste water treatment plants not otherwise specified
		Wastes from the preparation of water intended for human consumption or water for industrial use
20 00 00	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Separately collected fractions (except 15 01)
		Garden and park wastes (including cemetery waste)
		Other municipal wastes

Due to the diversity of substrates characteristics, so substrates could be classify into various categories according to various criteria such as: dry matter content (DM) or total solids content (TS), C / N ratio, methane yield and etc., Table (2.2) gives an overview of the characteristics of some digestible feedstock types. Substrates which contain DM content lower than 20 % are used for wet digestion (wet fermentation) this category includes animal slurries and manure besides various wet organic wastes from food industries. When the DM content is high up to 35 %, it is called dry digestion (dry fermentation), and it is mainly use for energy crops and silages (**Kossmann *et al.*, 1999; Bio Fuel Cells Concepts for Local Energy, 2000; Dennis and Burke, 2001; Lfu, 2007; Al Seadi *et al.*, 2008 and Hopwood, 2011**).

[6] The 6-digit code refers to the correspondent entry in the European Waste Catalogue (EWC) adopted by the European Commissions.

Table 2.2: The characteristics of some digestible feedstock types (author elaboration *cited in* **Al Seadi, 2001**)

Type of feedstock	Organic content	C / N ratio	DM (%)	VS % of DM	Biogas yield (m^3 / kg of VS)	Unwanted physical impurities	Other unwanted matters
Pig slurry	Carbohydrates, Proteins & lipids	3 - 10	3 - 8	70 - 80	0.25 - 0.50	Wood shavings, bristles, water, sand, cords & straw	Antibiotics, disinfectants
Cattle slurry	Carbohydrates, Proteins & lipids	6 - 20	5 - 12	80	0.20 - 0.30	Bristles, soil, water, Straw & wood	Antibiotics, disinfectants & NH_4^+
Poultry slurry	Carbohydrates, Proteins & lipids	3 - 10	10 - 30	80	0.35 - 0.60	Grit, sand & feathers	Antibiotics, disinfectants & NH_4^+
Stomach/ intestine content	Carbohydrates, Proteins & lipids	3 - 5	15	80	0.40 - 0.68	Animal tissues	Antibiotics & disinfectants
Whey	75 – 80 % lactose 20 – 25 % protein	-	8 - 12	90	0.35 - 0.80	Transportation impurities	-
Conc.[7] whey	75 – 80 % lactose 20 – 25 % protein	-	20 - 25	90	0.80 - 0.95	Transportation impurities	-
Flotation sludge	65 – 70 % proteins 30 – 35 % lipids	-	-	-	-	Animal tissues	Heavy metals, Disinfectants & organic pollutants
Ferment & slops	Carbohydrates	4 -10	1 - 5	80 - 95	0.35 - 0.78	Non-degradable fruit remains	-
Straw	Carbohydrates & lipids	80 - 100	70 - 90	80 - 90	0.15 - 0.35	Sand & grit	-
Garden wastes	-	100 - 150	60 - 70	90	0.20 - 0.50	Soil & cellulosic components	Pesticides
Grass	-	12 - 25	20 - 25	90	0.55	Grit	Pesticides
Grass silage	-	10 - 25	15 - 25	90	0.56	Grit	-
Fruit wastes	-	35	15 - 20	75	0.25 - 0.50	-	-
Fish oil	30 – 50 % lipids	-	-	-	-	-	-
Soya oil / margarine	90 % vegetable oil	-	-	-	-	-	-
Alcohol	40 % alcohol	-	-	-	-	-	-
Food remains	-	-	10	80	0.50 - 0.60	Bones, plastic	Disinfectants
Organic household waste	-	-	-	-	-	Plastic, metal, stones, Wood & glass	Heavy metals & organic pollutants
Sewage sludge	-	-	-	-	-	-	Heavy metals & organic pollutants

[7] Concentrated

Substrates contain high amounts of lignin, cellulose and hemicelluloses need to pre-treatment to reduce lignin content at substrate and enhance the digestibility of cellulose and hemicelluloses crops (**Bio Fuel Cells Concepts for Local Energy, 2000; Al Seadi *et al.*, 2008 and Frandsen *et al.,* 2011**).

The production quantity of methane considers one of the most important criteria to evaluate the different types of AD substrates (Fig. 2.2). The animal manure has relatively low methane productivity, so that in practical application the animal manure is not digested alone, but mixed with other co-substrates, which have high methane productivity, in order to enrich the biogas production. Mainly, co-substrates, which added for co-digestion with manure and slurries, are oily residues from food, fishing and feed industries, alcohol wastes, from brewery and sugar industries, or even specially cultivated energy crops (**British Biogen, 2000; Monnet, 2003 ; Patel, 2006 and Al Seadi *et al.*, 2008**).

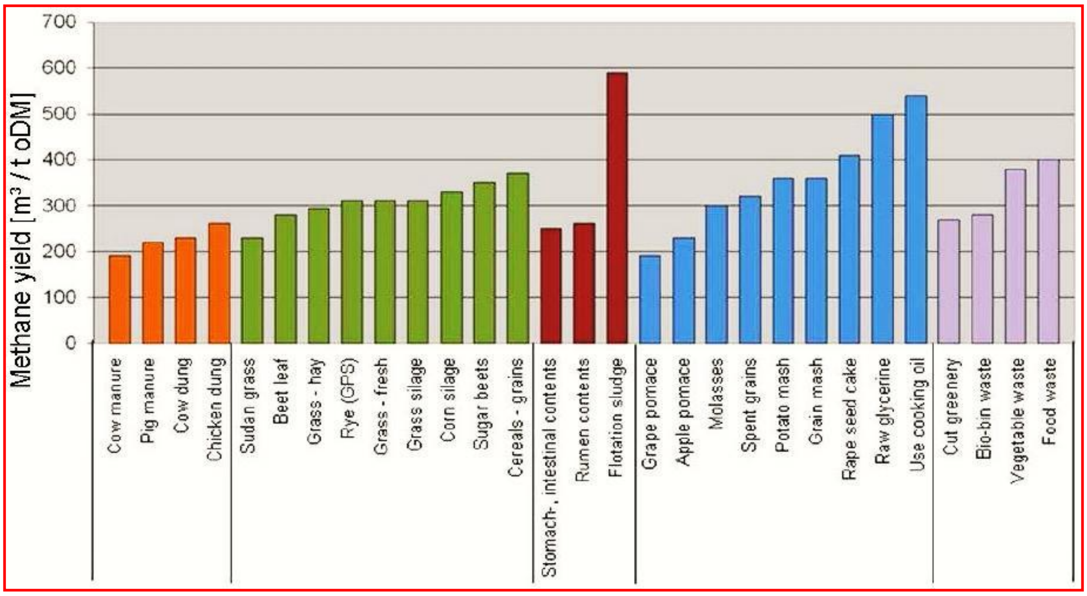

Fig. 2.2: Specific methane yield from different types of AD substrates (as *cited in* **PRAßL, 2007** *cited in* **Al Seadi *et al.*, 2008**)

The substrates of AD could contain some contaminants (such as chemical, biological or physical pollutants). The common contaminants for some types of AD substrates are illustrated in Table (2.3). Animal wastes require special attention if used as substrate for AD. Regulation 1774 / 2002 of the European parliament laid down health rules regarding handling and utilization of animal by-products not intended for human consumption. Quality control of all AD substrates types is essential in order to ensure a safe recycling of digestate as fertilizer. (**Al Seadi, 2001; European Parliament, 2002; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

Table 2.3: Problematic materials, contaminants and pathogens of some AD substrates categories (author elaboration *cited in* **Al Seadi *et al*., 2008**)

<table>
<tr><th>Risk / Feedstock</th><th>Safe</th><th>Hygienic risks</th><th>Contains problem materials</th><th>Risks of contaminants</th></tr>
<tr><td>Communal residue material</td><td>Greenery and grass cuttings</td><td>-</td><td colspan="2">Bio-waste and roadside greenery</td></tr>
<tr><td>Industrial residue materials</td><td>Vegetable waste, mash and etc.</td><td colspan="2">Expired foodstuff and foods with transport damage</td><td>Residue from vegetable oil production</td></tr>
<tr><td rowspan="2">Agricultural residues</td><td colspan="2">Fluid dung and solid dung</td><td>-</td><td>Copper and zinc</td></tr>
<tr><td>Beet leaves and straw</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Renewable raw materials</td><td>Corn silage and grass silage</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Slaughter wastes</td><td>-</td><td>Rumen, stomach-intestinal contents, separated fats, blood flour and etc.</td><td>-</td><td>Separated-fats</td></tr>
<tr><td>Miscellaneous</td><td>-</td><td colspan="2">Industrial kitchen waste and household waste</td><td>-</td></tr>
</table>

2.1.2. Theory of AD

AD is a microbiological process of anaerobic decomposition (in the absence of oxygen) of the organic matter. The main outputs of this process are biogas and digestate. Biogas is a combustible gas, mainly consists of methane and carbon dioxide mixture. Digestate is the decomposed substrate, resulted from the production of biogas (**Kossmann *et al.*, 1999; Bio Fuel Cells Concepts for Local Energy, 2000; British Biogen, 2000; Al Seadi, 2001; Dennis and Burke, 2001; Monnet, 2003; Patel, 2006; Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009 and Crolla and Kinsley, 2011**).

During AD, so little heat is produced on the contrary of the aerobic decomposition (in presence of oxygen), like it is the case of composting. The energy, which is chemically bounded in the substrate, remains mainly in the produced biogas, in form of methane (**British Biogen, 2000; Monnet, 2003; Patel, 2006 and Baldwin *et al.*, 2009**).

The biogas formation is a result of sequential steps, in which the raw materials is continuously broken down into smaller units. Specific species of micro-organisms are involved in each separately step. These micro-organisms decompose the products sequentially from the previous steps. The simple diagram of the AD process, illustrated in Fig. (2.3), focuses on the four main process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (**Kossmann *et al.*, 1999; Al Seadi, 2001; Dennis and Burke, 2001; Batstone *et al.*, 2002; Monnet, 2003; Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009 and Donoso-Bravo *et al.*, 2009**).

The steps of AD process (Fig. 2.3) runs parallel in time and space, in the digester. The speed of the decomposition process is determined by the slowest Interaction of the chain (Fig. 2.4). During decomposition of vegetable substrates, which containing cellulose, hemi-cellulose and lignin, hydrolysis is the slowest Interaction, which determined the speed of process. During hydrolysis step, relatively small amount of biogas is produced. Biogas production reaches its peak during methanogenesis (**Al Seadi, 2001; Batstone *et al.*, 2002; Monnet, 2003; Baldwin *et al.*, 2009; Donoso-Bravo *et al.*, 2009 and WTERT, 2009**).

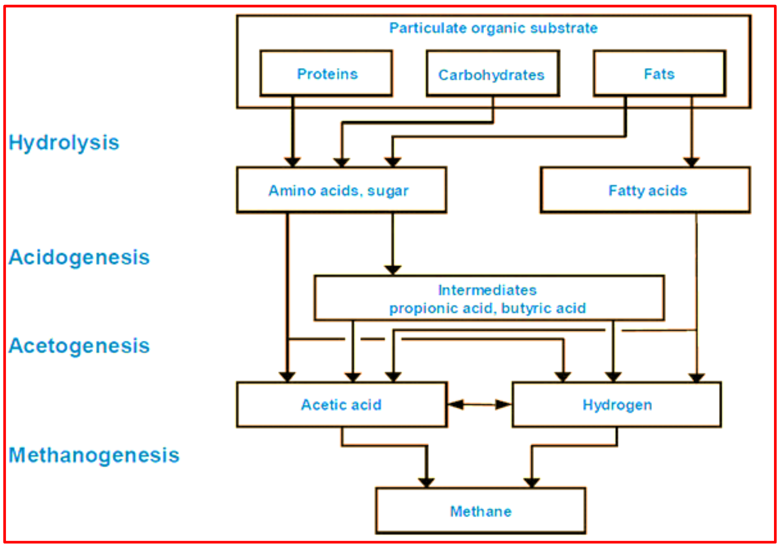

Fig. 2.3: The main steps of AD process (as *cited in* **WTERT, 2009**)

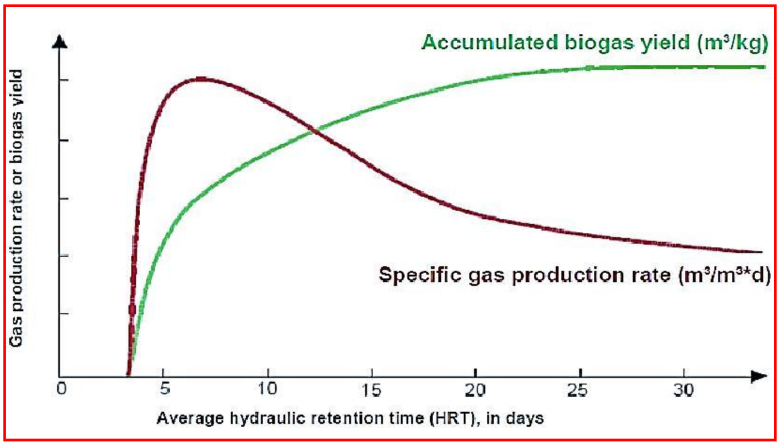

Fig. 2.4: Biogas yield after addition of substrate-batch test

(as *cited in* **Lfu, 2007** *cited in* **Al Seadi *et al*., 2008**)

2.1.2.1. Hydrolysis

Theoretically hydrolysis is the first step of AD, during this step the complex organic matters (polymers) are decomposed into smaller units (mono- and oligomers). During hydrolysis step, polymers like carbohydrates, lipids, nucleic acids and proteins are converted to glucose, glycerol, purines and pyridines (**Al Seadi, 2001; Batstone *et al.*, 2002; Monnet, 2003; Baldwin *et al.*, 2009; Donoso-Bravo *et al.*, 2009 and WTERT, 2009**).

Hydrolytic microorganisms excrete hydrolytic enzymes, which converting biopolymers into simpler and soluble compounds as it is shown below:

Lipids ⎯⎯lipase⎯→ fatty acids, glycerol;

Polysaccharide ⎯⎯cellulase, cellobiase, xylanase & amylase⎯→ monosaccharide;

Proteins ⎯⎯protease⎯→ amino acids.

An assortment of microorganisms are involved in hydrolysis, those microorganisms excreted exoenzymes, which decompose the undissolved particulate material. The outputs from hydrolysis are further decomposed by the microorganisms involved and used for their own metabolic processes (**Al Seadi, 2001; Batstone *et al.*, 2002; Monnet, 2003; Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009; Donoso-Bravo *et al.*, 2009 and WTERT, 2009**).

2.1.2.2. Acidogenesis

During acidogenesis, the outputs of hydrolysis are converted to methanogenic substrates by acidogenic (fermentative) bacteria. Simple sugars, amino acids and fatty acids are degraded into acetate, carbon dioxide and hydrogen (70 %) as well as into volatile fatty acids (VFA) and alcohols (30 %) (**Al Seadi, 2001; Batstone *et al.*, 2002; Monnet, 2003; Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009; Donoso-Bravo *et al.*, 2009 and WTERT, 2009**).

2.1.2.3. Acetogenesis

During acetogenesis, outputs from acidogenesis are converted into methanogenic substrates (outputs from acidogenesis can't be directly converted to methane by methanogenic bacteria during acidogenesis step). During methanogenesis, hydrogen is converted into methane by bacteria. Acetogenesis and methanogenesis are usually run parallel, as symbiosis of two groups of organisms (**Al Seadi, 2001; Batstone *et al.*, 2002; Monnet, 2003; Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009; Donoso-Bravo *et al.*, 2009 and WTERT, 2009**).

2.1.2.4. Methanogenesis

The production of methane and carbon dioxide from intermediate outputs is carried out by methanogenic bacteria. 70 % of the formed methane originates from acetate, while the remaining 30 % is produced from conversion of hydrogen (H) and carbon dioxide (CO_2), according to the following equations:

$$\textit{Acetic acid} \xrightarrow{\textit{methanogenic bacteria}} \textit{methane + carbon dioxide;}$$

$$\textit{Hydrogen + carbon dioxide} \xrightarrow{\textit{methanogenic bacteria}} \textit{methane + water.}$$

Methanogenesis is a critical step in the entire anaerobic digestion process. Methanogenesis is severely affected by operation conditions. Composition of feedstock, feeding rate, temperature, and pH are examples of factors influencing the methanogenesis process. Digester overloading, temperature changes or large entry of oxygen can result in termination of methane production (**Al Seadi, 2001; Batstone *et al.*, 2002; Monnet, 2003; Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009; Donoso-Bravo *et al.*, 2009 and WTERT, 2009**).

2.1.3. Factors controlling the AD

There are some vital parameters, which control the efficiency of AD, thus it is crucial provide appropriate conditions for growing of anaerobic microorganisms. The growth and activity of anaerobic microorganisms are significantly affected by surrounding conditions such as exclusion of oxygen, constant temperature, pH-value, nutrient supply, stirring intensity, moreover presence and amount of inhibitors (*e.g.* ammonia). The methane bacteria are fastidious anaerobes, so that the presence of oxygen into the digestion process must be strictly avoided (**Kossmann *et al.*, 1999; Dennis and Burke, 2001 and Al Seadi *et al.*, 2008**).

2.1.3.1. Temperature

The AD process could be done at different ranges of temperatures, the AD according to temperature classify into three ranges: psychrophilic, mesophilic, and thermophilic (see Table 2.4). There is a direct relation between the process temperature and the hydraulic retention time (HRT) (**Massart *et al.*, 2008; Baldwin *et al.*, 2009; Vindis *et al.*, 2009; Hopwood, 2011 and Cioabla *et al.*, 2012**).

Table 2.4: Thermal stages and typical hydraulic retention times (author elaboration *cited in* **Al Seadi *et al.*, 2008**)

Thermal stage	Process temperatures (°C)	HRT (day)
Psychrophilic	< 20	From 70 to 80
Mesophilic	From 30 to 42	From 30 to 40
Thermophilic	From 43 to 55	From 15 to 20

Stability of the temperature is crucial for AD process. In practice, the temperature of process is selected according to the type of feedstock used. The necessary temperature of process is usually generated by floor or wall heating systems, inside the digester. Fig. (2.5) illustrated the rates of relative biogas production depending on temperature and hydraulic retention time (**Biogas Process for Sustainable Development, 1992; Monnet, 2003; Massart *et al.*, 2008; Baldwin *et al.*, 2009; Vindis *et al.*, 2009; Hopwood, 2011 and Cioabla *et al.*, 2012**).

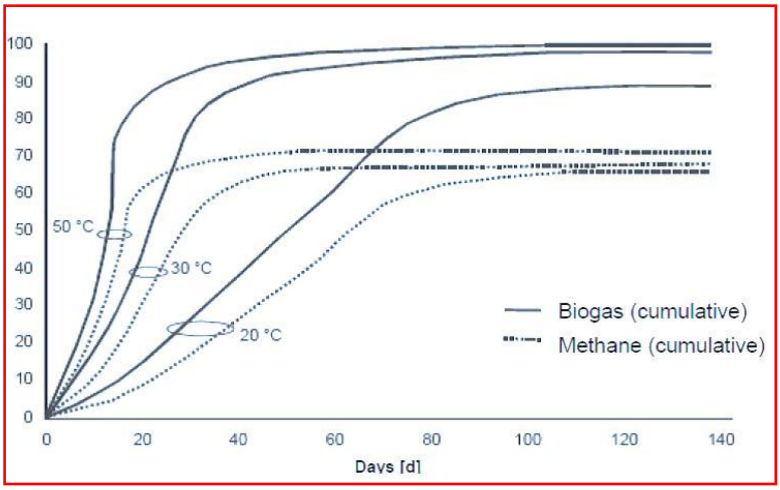

Fig. 2.5: Relative yield of biogas, depending on temperature and hydraulic retention time (as *cited in* **Lfu, 2007** *cited in* **Al Seadi *et al.*, 2008**)

According to **Al Seadi *et al.* (2008); Baldwin *et al.* (2009) and Vindis *et al.* (2009)** the advantages of thermophilic process compared to psychrophilic and mesophilic processes:

- More effective for pathogens sterilization;
- Growth rate of methanogenic bacteria is increasing at high temperature;
- Reduced retention time of AD process, making the process faster and more efficient;
- Better decomposition of solid substrates and better substrate utilization;
- Better possibility for separating liquid and solid fractions.

The thermophilic process also has some disadvantages (**Al Seadi *et al.*, 2008; Baldwin *et al.*, 2009 and Vindis *et al.*, 2009)**:

- Larger degree of imbalance;
- Larger energy demand due to high temperature;
- Higher risk of ammonia inhibition.

2.1.3.2. PH-value

The PH-value is the measure of acidity / alkalinity of a solution and is expressed in parts per million (ppm). The PH value of the AD substrate affects on the growth rate of methanogenic microorganisms, and also affects on the decomposition of some important compounds for the AD process (ammonia, sulphide, organic acids). The methane formation occurs within relatively narrow PH interval, from 5.5 to 8.5, with an optimum interval from 7.0 to 8.0 for most methanogens. Acidogenic microorganisms usually have lower value of optimum PH (**Kossmann *et al.*, 1999; Dennis and Burke, 2001; Monnet, 2003; Lfu, 2007 and Al Seadi *et al.*, 2008**).

The value of pH in AD process is mainly controlled by the bicarbonate buffer system. Therefore, the PH value inside digesters depends on the partial pressure of CO_2 and on the concentration of alkaline and acid components in the liquid phase. If accumulation of base or acid occurs, the buffer capacity counteracts these changes in PH, up to a certain level. When the buffer capacity of the system is exceeded, drastic changes in PH-values occur, completely inhibiting the AD process. For this reason, the PH-value is not recommended as a stand-alone process monitoring parameter (**Dennis and Burke, 2001; Monnet, 2003; Lfu, 2007**).

2.1.3.3. Ammonia

Ammonia (NH_3) has a significant role in the AD process. NH_3 is an important nutrient, serving as a precursor to foodstuffs and fertilizers and is normally encountered as a gas, with the characteristic pungent odor. Proteins are the main source of ammonia for the AD process. Too high concentration of ammonia inside the digester, is considered inhibit for AD process, due to methanogenic bacteria are especially sensitive to ammonia inhibition. This is common to AD of animal slurries, due to their high concentration of ammonia, originating from urine. For its inhibitory effect, ammonia concentration should be kept below 80 mg / l. (**Kossmann *et al.*, 1999; British Biogen, 2000; Dennis and Burke, 2001; Ohio State University Extension, 2006; Al Seadi *et al.*, 2008 and Westerma *et al.*, 2008**).

2.1.3.4. Nutrients

Sufficient concentration of nutrients is required to achieve optimum growth of bacteria. The carbon to phosphorus ratio should be less than 187. A non-lignin C / N ratio from 20 to 25 is optimum for digester performance. Typically, excreted manure has a C / N ratio around 10 (**British Biogen, 2000; Dennis and Burke, 2001; Monnet, 2003; Ohio State University Extension, 2006; Al Seadi *et al.*, 2008 and Balasubramaniyam *et al.*, 2008**).

2.1.3.5. C / N ratio

Microorganisms need both nitrogen and carbon for composition their cells. Experiments indicated that metabolic activity of methanogenic bacteria can be optimized at a C / N ratio range from 8 to 20 (see Table 2.2), whereby the optimum point varies from case to case, depending on the nature of the substrate (**Kossmann *et al.*, 1999; Al Seadi, 2001; Dennis and Burke, 2001; Lehtomäki, 2006; Al Seadi *et al.*, 2008 and Biogas Training Center, 2011**).

2.1.3.6. Toxic Materials

Toxic materials such as fungicides, antibacterial agents and heavy metals (iron, cobalt, copper, manganese, molybdenum, and zinc) can have an adverse effect on anaerobic digestion. The AD process can deal with small quantities of toxic materials without negative affect on the efficiency of AD process (**Steffen *et al.*, 1998; British Biogen, 2000; Dennis and Burke, 2001; Monnet, 2003 and Nels, 2011**).

2.1.3.7. Agitation (stirring)

Many types of substrates and various types of AD reactors require some sort of substrate agitation or mixing in order to maintain process stability in the digester. According to **Kossmann *et al.* (1999); Monnet (2003) and Massart *et al.* (2008)** the most important objectives of agitation are:

- Mixing of fresh substrate and bacterial population (inoculation);
- Preclusion of scum formation and sedimentation;
- Avoidance of pronounced temperature gradients within the digester;
- Provision of a uniform bacterial population density;
- Prevention of the formation of dead spaces that would reduce the effective digester volume.

2.1.3.8. Dilution

Dilution with water required to reduce the concentration of certain constituents such as nitrogen and sulfur that produces ammonia and hydrogen sulfide, which are inhibitory to the anaerobic digestion process. High solids digestion creates high concentrations of end products that inhibit anaerobic decomposition. Therefore, some dilution can have positive effects. The best reduction efficiencies occur at concentrations of approximately 6 to 8 % total solids (**Steffen *et al.*, 1998; Dennis and Burke, 2001; Monnet, 2003 and Ndegwa *et al.*, 2005**).

2.1.4. Operational parameters controlling the AD

2.1.4.1. Hydraulic retention time (HRT)

The HRT is the average time interval when the substrate is kept inside the digestion chamber. HRT is correlated to the digestion chamber volume and the volume of substrate fed per time unit, according to the following equation (**Steffen *et al.*, 1998; Kossmann *et al*., 1999; Dennis and Burke, 2001; Monnet, 2003 and Al Seadi *et al*., 2008**):

$$HRT = \frac{VDC}{DMU} \qquad (2.1)$$

Where:

HRT = Hydraulic Retention Time (day);
VDC = Inner-volume of digestion chamber (m^3);
DMU = Discharge of pumping and mixing unit (m^3 / day).

The retention time of substrate in the digester is dependent upon the type and characteristics of substrate. Generally, although most wet AD plants operate on a continuous basis, the aim would be for the material to remain within the digester from 20 to 40 days (see Table 2.4). Longer retention times are possible, but require greater tank capacity and see a reduction in biogas output over time. As a greater proportion of solid material, such as crops, is added the retention time needs to be increased to achieve optimum biogas output and material throughput (**Biogas Process for Sustainable Development, 1992; Patel, 2006; United States Department of Agriculture, 2007; Massart *et al.*, 2008; Baldwin *et al.*, 2009 and Hopwood, 2011**).

2.1.4.2. Solids retention time (SRT)

The SRT is important factor controlling the conversion of solids to gas. It is also important factor in maintaining digester stability. Although the calculation of solids retention time is often improperly stated, it is the quantity of solids maintained in the digester divided by the quantity of solids wasted each day. The SRT can be calculating according to the following equation (**Dennis and Burke, 2001; Lehtomäki, 2006; Massart *et al.*, 2008 and Baldwin *et al.*, 2009**):

$$SRT = \frac{VDC \, . \, TSC}{QDW \, . \, TSW} \qquad (2.2)$$

Where:

SRT = Solids retention time (day);
VDC = Inner-volume of digestion chamber (m^3);
TSC = Total solids concentration in the digester (kg / m^3);
QDW = Daily quantity of wasted (m^3 / day);
TSW = Total solids concentration of the waste (kg / m^3).

2.1.4.3. Digestion chamber loading

Digestion chamber (inside the digester) loading refers to the amount of feedstock (usually mass of total solids or volatile solids) feeding into the digestion chamber per day per m^3 of digestion chamber volume. Increasing the digestion chamber loading will reduce the digestion chamber size but will also reduce the percentage of volatile solids converted to gas. In general better digestion can be achieved at lower loadings. Thermophilic reactors appear to achieve greater conversions at high loadings while mesophilic reactors appear to achieve greater conversions at lower loadings. In typical anaerobic digester the digestion chamber loading is from 1 to 5 kg / m^3. day (**What Size Digester Do I Need, 1996; Bio Fuel Cells Concepts for Local Energy, 2000; Dennis and Burke, 2001; United States Department of Agriculture, 2007; Balasubramaniyam *et al.*, 2008; Massart *et al.*, 2008 and Westerma *et al.*, 2008**).

The digestion chamber loading can be calculated if the HRT and influent waste concentration is known according to the following equation:

$$LDC = \frac{CIW}{HRT} \qquad (2.3)$$

Where:

LDC = Digestion chamber loading (kg of TS or VS / m^3 of digestion chamber volume. day);

CIW= Influent waste concentration (kg of TS or VS / m^3 of digestion chamber volume);

HRT = Hydraulic Retention Time (day).

2.1.5. Evaluation parameters of biogas plants

A number of parameters, which illustrated in Table (2.5), can be used for evaluation of biogas plants and for comparing different systems (**Werner *et al.*, 1989; Kossmann *et al.*, 1999 and Al Seadi *et al.*, 2008**).

There are two main categories of parameters can be found:

- Operating data, this can be determined by measurement;
- Parameters, which can be calculated from the measured data.

Table 2.5: Operational parameters of biogas plants (author elaboration *cited in* **Al Seadi *et al.*, 2008)**

Parameter	Symbol	Unit	Determination
Temperature	T	°C	Measurement during operation
Operational pressure	P	bar	Measurement during operation
Capacity, throughput	V	m^3/day; ton/day	Measurement
Reactor volume	V_R	m^3	Determined by construction
Gas quantity	V per day V per year	m^3/day	Measurement during operation and conversion to Nm³
Retention time (hydraulic, minimum guaranteed)	HRT MGRT	day	Calculation from operating data
Organic load		kg or ton/m³.day	Calculation from operating data
Methane concentration in biogas	CH_4	%	Measurement during operation
Specific biogas yield		%	Calculation from operating data
Specific biogas production		m^3/m^3	Calculation from operating data
Gross energy		kWh	Determination from the quantity of biogas and methane concentration
Electricity production		kWh	Measurement at the BTTP generator
Output to grid		kWh	Measurement after the BTTP generator
Efficiency of BTTP	η	%	Calculation from operating data
Station supply thermal / electric		kWh	Basis of planning, afterwards measurement during operation
Specific station supply thermal /electric		kWh/m³ Input kWh/GV	Calculation from operating data
Energy production		kWh	Sum of energy that can be sensibly utilized. Calculation from operating data
Plant efficiency	η	%	Net energy drawn from gross energy
Availability		%	Percentage of hours in a year in which a plant is fully functioning
Utilization		%	Ratio of the real quantity input to the projected capacity
Total investment		€	All expenses caused by the biogas plant
Subsidies		€	Pre-determined
Subsidy percentage		%	Percentage of all subsidies in relation to total investments
Specific investments		€/m³ reactor €/GV	Only sensible when primarily manure from animal husbandry is used
Specific treatment costs		€/m³ Input; €/GV	Calculation

2.2. Different technologies of agricultural biogas plants

There are several technical and operational alternatives to choose from the different technologies applied from smaller to larger scale according to factors, such as investment and operational costs, workload, the end-use of digestate intended and goals for energy production etc. In small household plants very simple technological solutions are used. On farm-scale the technology becomes somewhat more elaborate, but the aim is to still keep it simple and easy-to-use, while on large, centralized scale the biogas plant may consist of several different processing units the operation of which requires more monitoring and knowhow (**Sasse, 1988; FAO, 1996; Kossmann *et al.*, 1999; Centre for Energy Studies Institute of Engineering, 2001; Buxton, 2010 and Hopwood, 2011**).

2.2.1. Different scales of agricultural biogas plants

There are differ sizes (scales) and technologies of agricultural biogas plants. Small and often self-made biogas plants are used in tropical countries for treating wastes from the household farming and cooking. In industrial countries with intensive agriculture the biogas plants are significantly bigger and more advanced, equipped with modern technology to increase digester capacity and to apply process control for stable operation (**Sasse, 1988; FAO, 1996; Kossmann *et al.*, 1999; Centre for Energy Studies Institute of Engineering, 2001; Al Seadi *et al.*, 2008; Buxton, 2010 and Hopwood, 2011**).

Generally, agricultural biogas plants can be classified into three different scales according to size:

- Household biogas plants;
- On-farm biogas plants;
- Centralized biogas plants.

2.2.1.1. Household-scale of biogas plants

Household biogas plants are small, very simple and manually operated (Fig. 2.6). This type of biogas plants can be effectively operated under warm climate conditions, while implementation in temperate to cold areas may require temperature control. The biogas yield from household biogas plants is usually using for cooking and lighting. For example in

China, there were 30 million biogas plants in rural areas until year 2010, most of them are household digesters with volume of 4 - 10 m^3, produces up to 2 m^3 of biogas per day (**Sasse, 1988; FAO, 1996; Kossmann *et al.*, 1999; Nagamani and Ramasamy, 1999; Centre for Energy Studies Institute of Engineering, 2001; Al Seadi *et al.*, 2008; Buxton, 2010 and World Energy Outlook, 2010**).

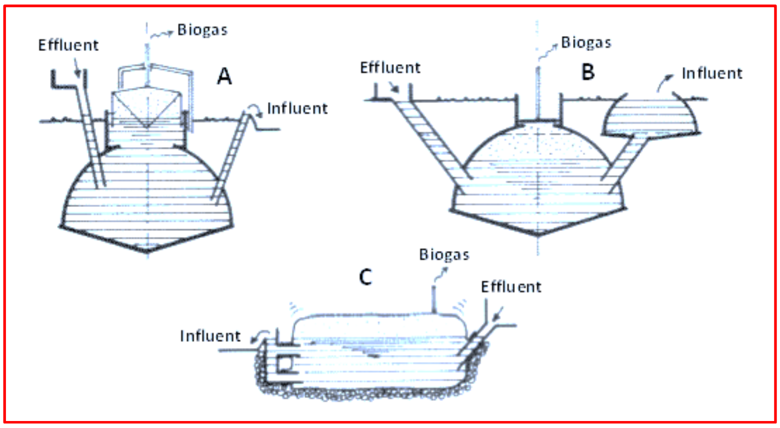

Fig. 2.6: Household-scale digesters: (A) Floating-drum plant, (B) Fixed-dome plant and (C) Balloon plant (author elaboration *cited in* **Sasse, 1988**)

2.2.1.2. Farm-scale of biogas plants (On-farm biogas plants)

Farm-scale biogas plants are integrates with crop production and / or with animal husbandry, with herbal biomass and manure as the usual feedstock. Farm-scale biogas plants have simple technology and basic automation to maintain a stable process, while larger biogas plants for farm cooperatives may also use more advanced and complex technologies. Agricultural biogas plants are classified into three categories according to electrical energy productive capacity of on-farm CHP unit (**Philip, 2005; Institut für Energetik und Umwelt *et al.*, 2006; Plöchl and Heiermann, 2006; Al Seadi *et al.*, 2008 and Hopwood, 2011)**:

- Small scale ≤ 70 kWh_{el};
- Medium scale 70 - 150 kWh_{el};
- Large scale 150 - 500 kWh_{el}.

According to the above classification, the small to medium scale would be applicable on single farms, while medium to large scale would most likely be of farm cooperatives (**Philip, 2005; Plöchl and Heiermann, 2006 and Hopwood, 2011**).

Farm-scale biogas plants usually aims to closing the energy and nutrient cycles in the farm and offer a good basis for sustainable energy supply. General scheme of a farm-scale biogas plant is illustrated in Fig. (2.7), with co-digestion of energy crops and manure slurry. The main products of the biogas plant in Fig. (2.7) are heat, electricity and digestate. Depending on the on-farm requirements and pricing situation for the energy, the energy produced is either used on-farm to replace energy from grid or sold to the grid (electricity and heating). Possibly other practices, such as biogas upgrading to bio-methane for fuel, reuse of fibers from manure for bedding and use of irrigation as a means of applying mechanically separated liquid fraction of digestate on fields, can be applied (**Centre for Energy Studies Institute of Engineering, 2001; Philip, 2005; Institut für Energetik und Umwelt *et al.*, 2006; Plöchl and Heiermann, 2006; Al Seadi *et al.*, 2008 and Hopwood, 2011**).

Farm cooperative biogas plants usually focus on closing nutrient cycles on the cooperating farms with possible re-division of the manure nutrients, i.e. farms with excess phosphorus may receive less phosphorus in digestate than they deliver the plant in the raw manure, while farms with phosphorus requirement receive more phosphorus in digestate than they deliver to the plant. Also in addition to animal farms, some farms in the cooperative may be crop producers, providing the plant with some crops and receiving digestate. For example in Germany, Denmark and Holland, many agricultural biogas plants use energy crops with less or no manure and use the digestate for the crop production. The energy produced in farm cooperative biogas plants is usually sold to the network (electricity networks and / or thermal networks) or utilized in adjacent companies, such as greenhouses. Biogas upgrading to bio-methane is also possible (**FAO, 1996; Philip, 2005; Institut für Energetik und Umwelt *et al.*, 2006; Al Seadi *et al.*, 2008 and Hopwood, 2011**).

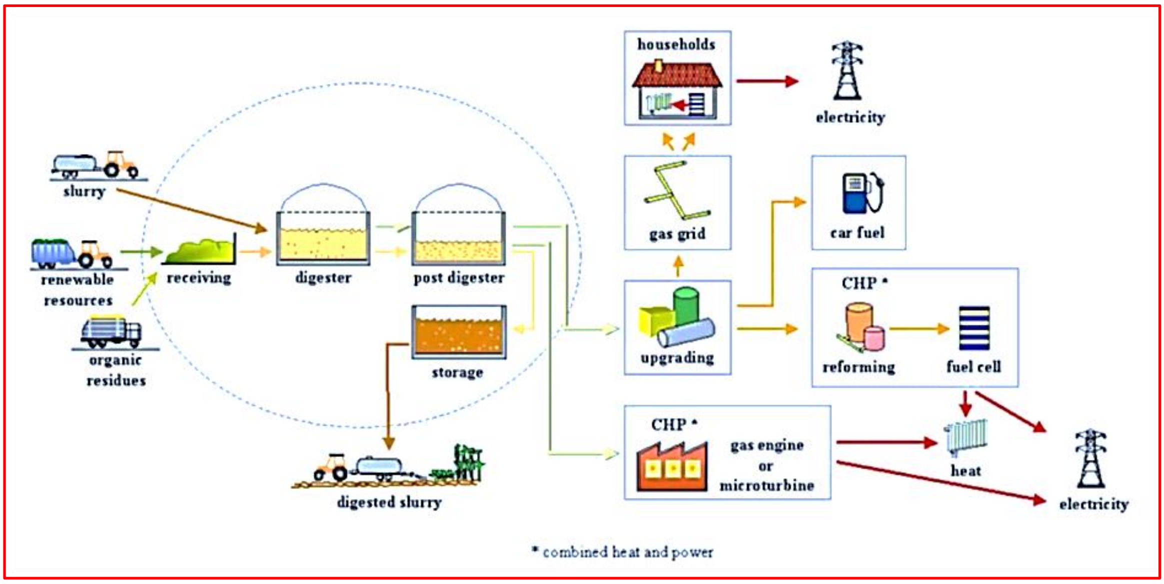

Fig. 2.7: Scheme of farm-scale biogas plant uses energy crops, manure slurry and organic residues as feedstock and including different pathways of biogas utilization (as *cited in* **Plöchl and Heiermann, 2006**)

2.2.1.3. Centralized-scale of biogas plants

In centralized biogas plants (Fig. 2.8), the technologies applied usually more complex than in biogas plants focusing on agricultural materials of one or a few farms. Moreover, the raw materials are often collected from several sources and the feed mixture may contain diverse materials from agriculture, municipalities and industry. The choice of technology varies case-specifically depending on the raw materials available, the aims of the processing (*e.g.* energy production, fertilizer production, stabilization of waste materials, reduction of environmental load), the costs for investment and operation, subsidy systems available, etc. Centralized biogas plants may produce heat or heat and power depending on the case-specific conditions, but the economy of scale may also make bio-methane production more attractive than in smaller biogas plants. Currently, on large farms or centralized plants have two or three digesters with volume of several thousands of cubic meters and CHP units with total electrical productive capacity from 500 to 1000 kWh_{el} (**Philip, 2005; Institut für Energetik und Umwelt *et al.*, 2006; Plöchl and Heiermann, 2006; Al Seadi *et al.*, 2008 and European Biomass Association, 2009**).

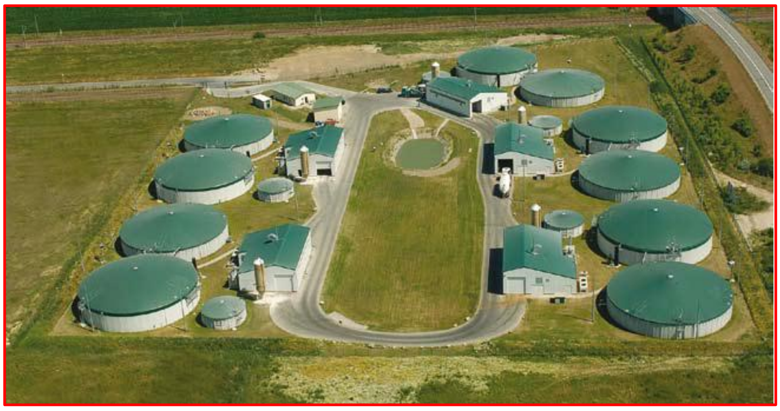

Fig. 2.8: Centralized biogas plant (as *cited in* **European Biomass Association, 2009**)

2.3. Main components of biogas plants

A biogas plant consists of several of components. The design of such a plant depends to a large extent on the types and amounts of feedstock supplied (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

The main processing steps in a biogas plant are illustrated in Fig. (2.9). the processing steps illustrated in italics are not common for agricultural biogas plants. The difference between dry and wet AD is only theoretical, since microbiological processes always take place in fluid media. The limit between dry and wet digestion is determined by the substrate pumpability. DM content (total solids) of substrate above 15 % that means the material is not pumpable and the AD in this case is defined as dry digestion, while DM content (total solids) of substrate is less 15 % the AD in this case is defined as wet digestion (**Dennis and Burke, 2001; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008 and Hopwood, 2011**).

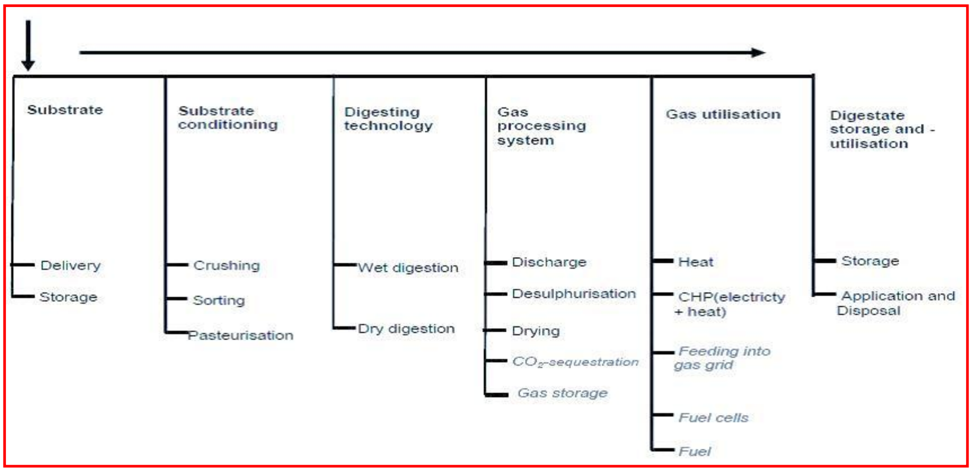

Fig. 2.9: Main processing steps of anaerobic technologies (as *cited in* **Lfu, 2007** *cited in* **Al Seadi** ***et al.,*** **2008**)

The main component of a biogas plant is the anaerobic digester, which integrates with the other components of biogas plant as illustrated in Fig. (2.10) (**Sasse, 1988; Kossmann** ***et al.*****, 1999; Dennis and Burke, 2001; Institut für Energetik und Umwelt** ***et al.*****, 2006; Lfu, 2007 and Al Seadi** ***et al.*****, 2008**).

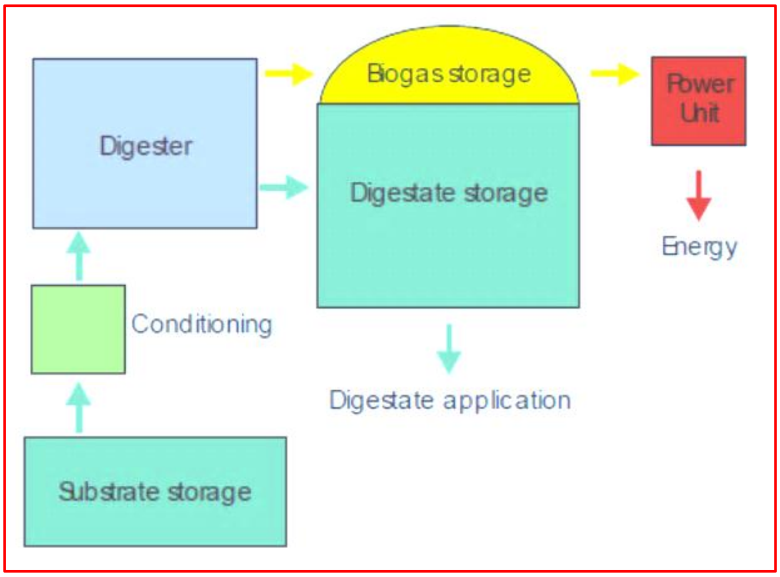

Fig. 2.10: Main components of biogas plant (author elaboration)

According to **Dennis and Burke (2001); Institut für Energetik und Umwelt** ***et al.*****, (2006); Lfu, (2007) and Al Seadi** ***et al*****. (2008)** in agricultural biogas plants, could distinguished four different processing stages, which illustrated in Figs. (2.11 & 2.12) as follows:

1. Pre-digestion stage (storage, conditioning, transport and insertion of feedstock) includes the storage tank for manure (2), the collection bins (3), the sanitation tank (4), the drive-in storage tanks (5) and the solid feedstock feeding system (6);
2. The anaerobic digestion (biogas production) stage includes the biogas production in the digester (7);
3. Storage and utilization of digestate stage includes the storage tank of digestate (10) and the utilization of digestate as fertilizer for agricultural purposes (11);
4. Storage and utilization of biogas stage (biogas storage, conditioning and utilization) includes the gas storage tank (8) and on-farm CHP unit (9).

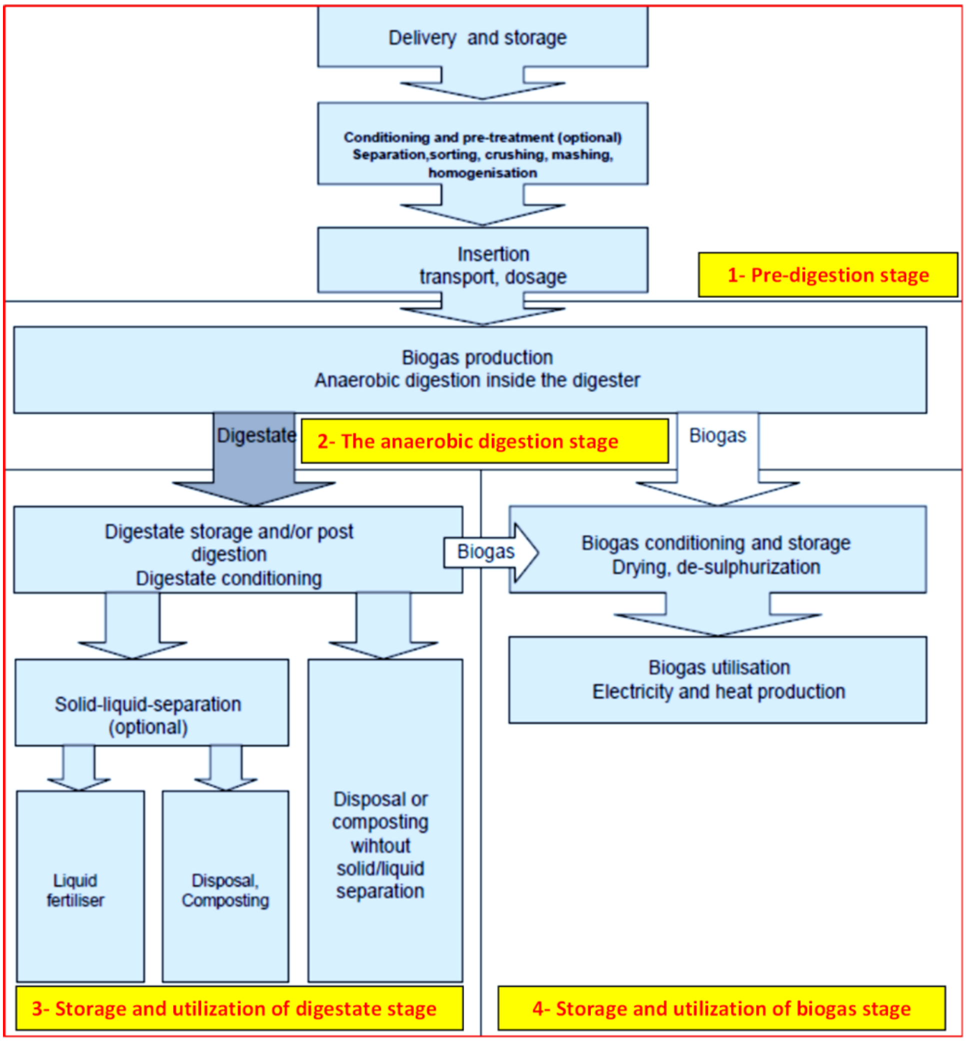

Fig. 2.11: Processing stages of agricultural biogas plants (author elaboration *cited in* **JÄKEL, 2002** *cited in* **Al Seadi *et al.*, 2008**)

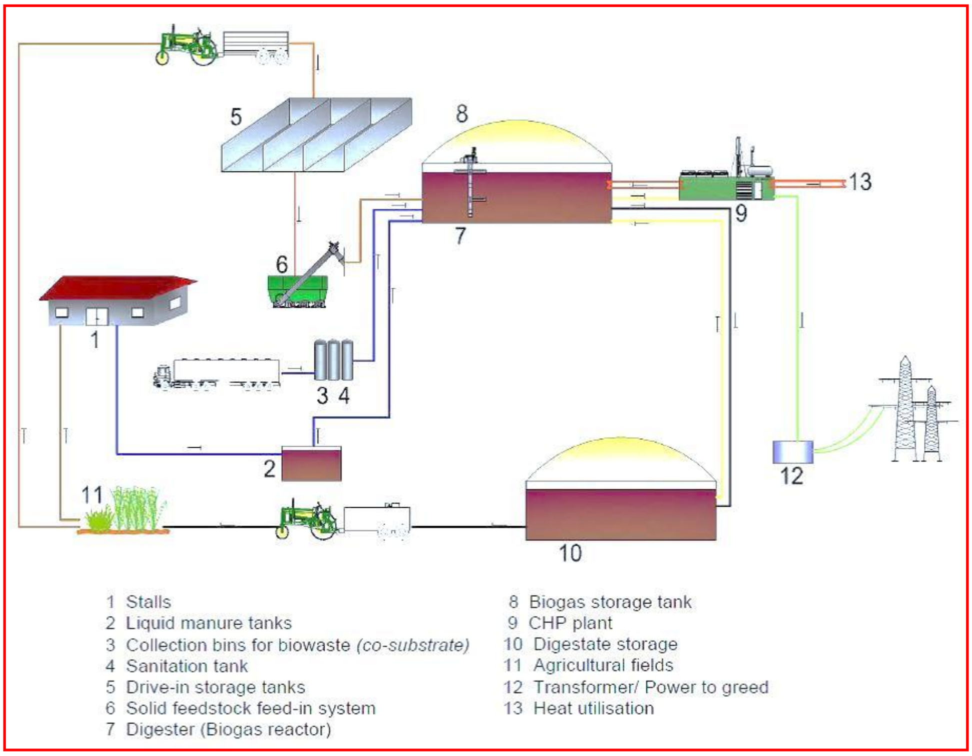

Fig. 2.12: Agricultural co-digestion biogas plant using manure and maize silage (as *cited in* **Lorenz, 2008** *cited in* **Al Seadi *et al.,* 2008**)

2.3.1. Feedstock handling system

2.3.1.1. Receiving unit of feedstock

Efficient transport and supply of feedstock (crop yield, by-products and manure) is important to ensure a stable and continuous supply of feedstock, of suitable quality and quantities. In many cases, the biogas plants receive additional feedstock (co-substrates), produced by neighboring farms, industries or households. Particular attention is needed for feedstock types classified as wastes, for which it may be necessary to fulfill regulatory obligations (depending on the waste category), as well as legal and administrative conditions. From the other hand, receiving unit equipped with some visual equipment (manual or robotic) for sorting and removal of bulky or potentially harmful items (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

2.3.1.2. Conditioning of feedstock

The main aims of conditioning are fulfill the demands of sanitation, increase feedstock digestibility and biogas yield (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Genesis Projects Corp, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

Conditioning of feedstock includes:

1. Feedstock sorting and separation of problematic material:

   This is an initial and necessary step for sorting and separating impurities and problematic materials from the feedstock substrate. Silage considers clean feedstock type, while manure and household wastes contains sands, stones and other physical impurities. These impurities are usually separated by sedimentation in storage tanks (in the case of sand sedimentation occur inside the digester) and they have to be removed from the bottom of the tanks from time to time. sometimes, could use pre-tank outfitted with special grills, which able to retain stones and other physical impurities before pumping the feedstock into the main storage tank, is used in many cases (**Lfu, 2007; Genesis Projects Corp, 2007; Al Seadi *et al.*, 2008 and; Rapport *et al.*, 2008**).

   Domestic wastes can contain various impurities (such as packing wastes of plastic, metals, wood, glass and other non-digestible materials, Fig. 2.13 right), which can cause clogging pipes, damage for pumps and even the digesters. These impurities could be removed by a separate collection system of household wastes (collect wastes in different Homogeneous groups *e.g.* organic, metals, plastic, paper and etc.) or they can be removed from bulk collected wastes by using mechanical sorters (Screens, rotating trommels, magnetic separation and etc.) and manual methods (use only for small quantities of wastes) (**Lfu, 2007; Genesis Projects Corp, 2007; Al Seadi *et al.*, 2008 and; Rapport *et al.*, 2008**).

Fig. 2.13: Mechanical system for separation solid wastes by using trommel (left) and problematic material, which was separated from feedstock (right) (as *cited in* **Rapport *et al.*, 2008**)

2. Crushing (particle size reduction):

   Crushing of feedstock material aims to prepare the surfaces of the particles for biological decomposition and the subsequent methane production. In general, the decomposition process is faster when the particle size is smaller. Particle size reduction can take place by mechanical and / or biological ways (**Genesis Projects Corp, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

3. Mashing:

   Mashing of feedstock is necessary in order to obtain feedstock with a higher moisture content, which can be handled by pumps. The advantage of using digestate for mashing lies in the reduction of fresh water consumption and in the inoculation of the substrate with AD micro-organisms from the digester. Use of fresh water should always be avoided due to high costs (**Al Seadi *et al.*, 2008**).

2.3.2. Storage of feedstock

Storage of feedstock mainly aims to compensate the seasonal fluctuations of feedstock supply and It is also facilitates mixing of different co-substrates for continuous feeding of the digester. The type of store depends on the type of feedstock. Types of stores can be mainly classified into bunker silos for solid feedstock (*e.g.* corn (maize) silage, Fig. 2.14) and storage tanks for liquid feedstock (*e.g.* liquid manure and slurries, Fig. 2.15). Usually, bunker silos have the capacity for store feedstock from six months up to more than one year, while storage tanks for manure have the capacity to store feedstock from several days up to several months. The dimensioning of the storage facilities is determined by the quantities to be stored, delivery intervals and the daily amounts fed into the digester (**Electrigaz Technologies Inc., 2007; Al Seadi *et al.*, 2008 and Kirchmeyr *et al.*, 2009**).

Fig. 2.14: Bunker silo, made of concrete and silage is covered by plastic foils (as *cited in* **Purdue Dairy Page, 2012**)

Fig. 2.15: Manure slurry tank (as *cited in* **Department of Environmental Protection, 2009**)

2.3.3. Systems of feeding

After storage and pre-treatment, AD feedstock is feed into the digester. There are two categories of feedstock, pumpable and non-pumpable. The pumpable feedstock category includes animal slurries and liquid organic wastes (*e.g.* flotation sludge, cattle wastes, fish oil). Feedstock types which are non-pumpable (e. g. fibrous materials, grass, maize silage, manure with high straw content) can be tipped / poured by a loader into the feeding system and then fed into the digester (*e.g.* by a screw pipe system) (**Electrigaz Technologies Inc., 2007; Genesis Projects Corp, 2007; Rapport *et al.*, 2008 and Kirchmeyr *et al.*, 2009**).

2.3.3.1. Pumps

Pumps used to transfer the pumpable feedstock substrate from the storage tank to the digester. There are two main types of pumps are frequently used: centrifugal (rotating) pumps (Fig. 2.16), and positive displacement pumps (rotary lobe pumps, Fig. 2.17 and progressing cavity pumps, Fig. 2.18). Centrifugal pumps are often submerged, but they can also be positioned in a dry shaft, next to the digester. Positive displacement pumps are more resistant to pressure than centrifugal pumps. They are self-sucking, works in two directions and reach relatively high pressures, with a diminished conveying capacity. However through their lower price, centrifugal pumps are more frequently chosen than positive displacement pumps (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007 and Al Seadi *et al.*, 2008**).

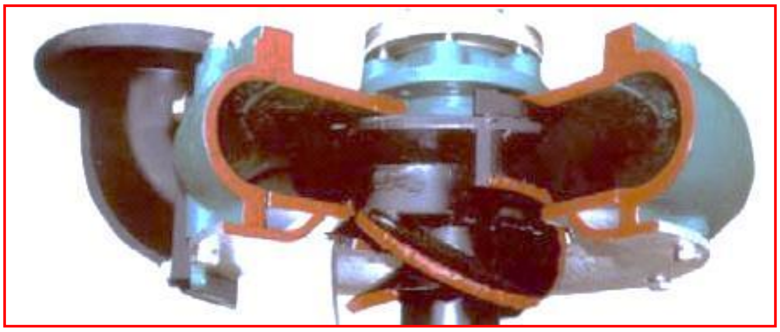

Fig. 2.16: Centrifugal (rotating) pump (as *cited in* **LfU, 2007**)

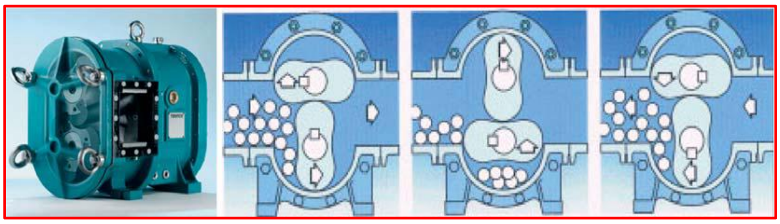

Fig. 2.17: Rotary lobe pump (as *cited in* **Institut für Energetik und Umwelt *et al.*, 2006**)

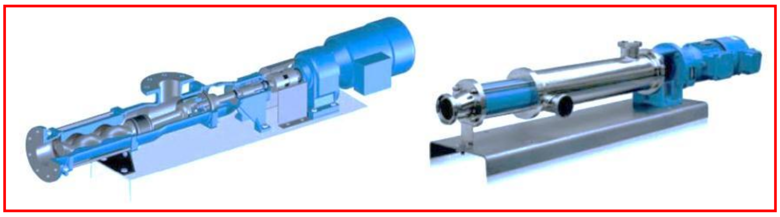

Fig. 2.18: Progressing cavity pump (as *cited in* **Lfu, 2007**)

The selection of appropriate pumps and pumping technology depends on the characteristics of the feedstock to be handled by pumps (type of material, DM content, particle size, and level of preparation). Pressure pipes, for filling or mixing, should have a diameter of at least 150 mm, while pressure free pipes, like overflow or outlet pipes, should have at least 200 mm for transporting manure and 300 mm if the straw content is high (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

The pumps should be equipped with stop-valves (Fig. 2.19), which allow feeding and emptying of digesters and pipelines. In many cases the entire feedstock transport within the biogas plant is realized by one or two pumps, located in a pumping station (Fig. 2.20) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

Fig. 2.19: Stop-valves (left) and pumping system (right) (as *cited in* **Rutz, 2006** *cited in* **Al Seadi *et al.*, 2008**)

Fig. 2.20: Pumping systems (as *cited in* **Vogelsang, 2012**)

2.3.3.2. Feeding equipment of solid feedstock

The feeding system of solid feedstock (*e.g*. grass, maize silage, manure with high straw content, vegetable residues etc.) consists of transport equipment (*e.g*. loaders and tractors, which transports feedstock from Bunker silo to containers, Fig. 2.21) and a conveying system (*e.g.* screw pipe conveyors, Fig. 2.22), which convey the feedstock from containers to digester automatically) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

Screw conveyors can be conveying feedstock in all directions. The only precondition is free of large stones and other physical impurities. For optimal operation, coarse feedstock should be crushed, in order to be fit into the screw windings. On the other hand there are three different systems of screw conveyors are commonly used: wash-in shaft, feed pistons and feed conveyor screws, which illustrated in Fig (2.23) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

Fig. 2.21: Loader feeding maize silage into the container (as *cited in* **Institut für Energetik und Umwelt *et al.*, 2006**)

Fig. 2.22: Screw pipe conveyors (as *cited in* **Wam India Private Limited, 2012**)

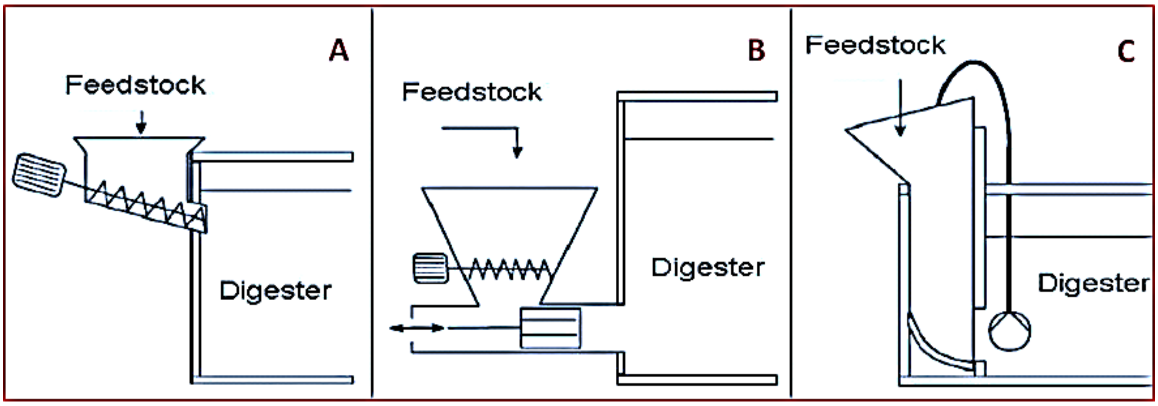

Fig. 2.23: (A) Wash-in shaft, (B) feed pistons and (C) feed conveyors system for feeding feedstock into the digester (author elaboration *cited in* **Institut für Energetik und Umwelt *et al.*, 2006**)

1. Wash-in shaft:

Wash-in shafts, load by front or wheel loaders, which allow large quantities of feedstock to be delivered any time, directly to the digester (Fig. 2.23 A) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

2. Feed pistons:

Feed pistons system (Fig. 2.23 B) uses for feed the feedstock directly into the digester by hydraulic cylinders, which push the feedstock through an opening in the wall of the digester. This system is use for reducing the risk of floating layer formation. This system is equipped with counter rotating mixing rollers for crush long fiber materials (*e.g.* air-dried silage) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

3. Feed screws conveyor:

Feed screw conveyor (Fig. 2.23 C) uses for feed the feedstock under the level of the liquid in the digester. This system has the advantage of preventing gas leaking during feeding process. This system sometimes equipped with mixing and crushing tools (Fig. 2.24) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

Fig. 2.24: Feeding container equipped with screw conveyor, mixing and crushing tools (as *cited in* **Agrinz, 2006** *cited in* **Al Seadi *et al.,* 2008**)

2.3.4. Heating system of digester

One of the most important conditions for high biogas production is keep constant temperature of AD process. Temperature fluctuations must be kept as low as possible, large fluctuations of temperature lead to imbalance of the AD process, and in worst cases lead to failure of process (**Electrigaz Technologies Inc., 2007; Al Seadi *et al.*; Kirchmeyr *et al.*, 2009 and Frandsen *et al.* ,2011**).

The reasons of temperature fluctuations are:

1. Add new feedstock, with different temperature of the process temperature;
2. Formation of various temperature layers due to insufficient heating system or stirring;
3. Extreme outdoor temperatures;
4. Failure of power system.

Digesters must be isolated and heated by external heating sources in order to achieve and maintain a constant temperature of AD process and to compensate of heat losses (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008 and Frandsen *et al.* ,2011**).

The feedstock heating can be done during the feeding process (pre-heating) or inside the digester, by heating system (Fig. 2.25). Pre-heating the feedstock during feeding process has the advantage of avoiding temperature fluctuations inside the digester. Many biogas plants use a combination of both types of feedstock heating (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008 and Frandsen *et al.*, 2011**).

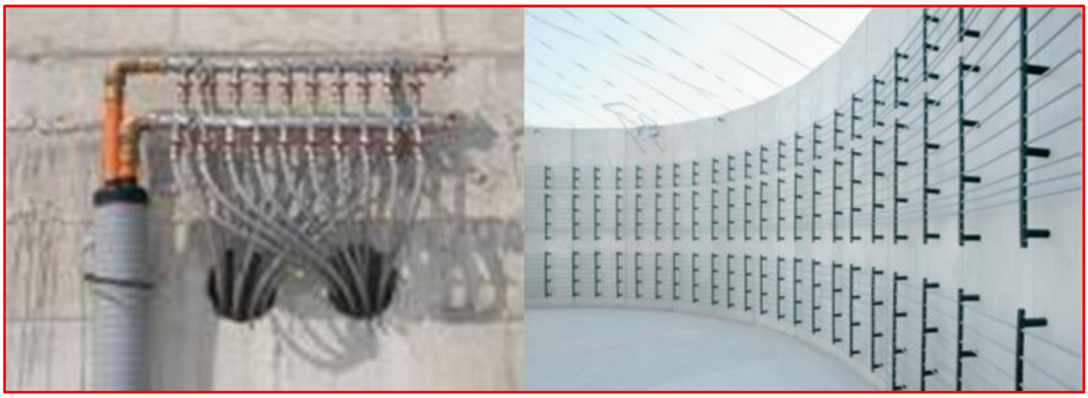

Fig. 2.25: Heating system of biogas plant (left) and heating pipes, installed inside the digester (right) (as *cited in* **REHAU, 2010**)

2.3.5. Digesters

Digester considers the core of biogas production system, where the decomposition of substrate occurs, in absence of oxygen for produce biogas. In European climates anaerobic digesters have to be isolated and heated. There are a various types of on-farm biogas digesters, which can be made of different materials such as concrete, steel, brick or plastic, shaped like silos, troughs, basins or ponds, and they may be placed underground or on the surface. The size of digesters varies from few cubic meters in the case of small household installations to several thousands of cubic meters, like in the case of large commercial plants, often with several digesters (**Kossmann *et al.*, 1999; Dennis and Burke, 2001; Lfu, 2007 and Al Seadi *et al.*, 2008**).

The selection of biogas digester depending on the dry matter content of the digested substrate. There are two AD technologies systems: wet digestion (liquid digestion), when the average dry matter content (DM) of the substrate is less than 15 % and dry digestion (solid digestion), when the DM content of the substrate is more than 15 % (usually from 20 to 40 %). Wet digestion is applied for feedstock like manure and sewage sludge, while dry digestion is applied for solid animal manure, with high straw content, household waste and solid municipal bio-waste, green cuttings and grass from landscape maintenance or energy crops (**Electrigaz Technologies Inc., 2007; Al Seadi *et al.*, 2008; Rapport *et al.*, 2008 and Kirchmeyr *et al.*, 2009**).

There are several different types of digesters technologies uses for agricultural biogas plants as illustrated in Tables (2.6 and 2.7):

Table 2.6: Main characteristics of anaerobic digesters technologies in agricultural biogas plants (author elaboration *cited in* **Institut für Energetik und Umwelt *et al.*, 2006 and Lfu, 2007**)

Characteristics	Technologies
Construction of digester	Covered lagoon, plug flow, complete mix, fixed film, UASB, vertical, Horizontal and etc.
Temperature in digester	Psychrophilic, mesophilic and thermophilic
Environment in digester	Wet and dry
Process stages	one-stage, two-stages and multiple stages
Loading (feeding) strategy	batch, continuous and semi-batch

Table 2.7: Comparison between different technologies of agricultural anaerobic digesters (author elaboration *cited in* **Electrigaz Technologies Inc., 2007**)

Technology	Digester type	Feedstock type	HRT (day)	biogas yield	Technology level
Wet digestion	Covered lagoon	Thin manure	20 - 200	Poor	Low
	Plug flow	Thick manure	20 - 40	Poor	Low
	Complete mix	Liquid & solid	20 - 80	Good	Medium
	Fixed film	Liquid	1 - 20	Good	High
	UASB	Liquid	0.5 - 2	Good	High
Dry digestion	Batch	Agricultural and municipal feedstock	20-30	Good	Medium
	Vertical		20 - 40	Good	High
	Horizontal		20 - 40	Good	High

2.3.5.1. Wet anaerobic digesters

Wet digesters systems are used substrate, which contains adequate fluid to be pumped (less than 15 % dry matter). On the other hand wet digesters can also digest solid feedstock, if they are equipped with adequate feeding equipment of solid feedstock. Bacterial decomposition of solids ensures that the substrate inside the digester remains liquid (**Kossmann *et al.*, 1999; Dennis and Burke, 2001; Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Rapport *et al.*, 2008 and Kirchmeyr *et al.*, 2009**).

A- Batch systems:

Wet digesters can run in batches or continuously. In batch systems the digesters are filled, mixed, left to digest, partially emptied and refilled. They are not emptied completely to ensure inoculation of fresh feedstock batches with bacteria from the previous batch. Batch systems works in one-stage or two-stages. These systems exist, but they are not common (**Dennis and Burke, 2001; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

B- Continuous systems:

Continuous systems are digesters that are fed daily and produce digestate daily. Continuous systems works in one-stage (wet or dry) or two-stages (wet-dry or dry-wet) or multiple stages. There are many types of continuous wet digesters (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**):

1-Covered lagoon digester:

Usually consists of a rectangular earthen lagoon covered with a flexible membrane to collect biogas (Fig. 2.26). Feedstock needs to be thin (contains less than 3 % of DM). The covered lagoon digester may be mixed with recirculation but is generally not mechanically mixed. Feedstock enters at one end, pushing substrate out through an overflow pipe, maintaining a consistent liquid level. The lagoons operate at psychrophilic or ground temperatures. Consequently, the reaction rate is affected by seasonal variations in temperature. The residence time of substrate (HRT) from 20 to 200 days (**Dennis and Burke, 2001; Covered Lagoon, 2003 and Electrigaz Technologies Inc., 2007**).

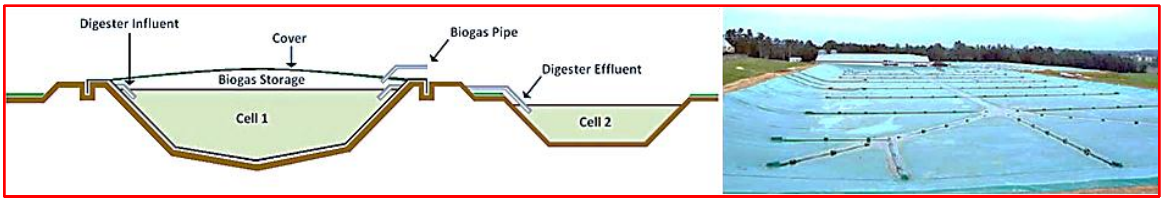

Fig. 2.26: Covered lagoon digester (as *cited in* **Covered Lagoon, 2003**)

Main components:

- Solids separator;
- Usually two lagoons: primary (covered) and secondary (volume storage);
- Floating lagoon cover;
- Biogas utilization system.

Advantages:

- Inexpensive;
- Simple and easy to install;
- Low technology applied compared with more mechanical systems.

Disadvantages:

- Requires significant area;
- Poor mixing of feedstock;
- Poor yield of biogas;
- Has a high HRT;
- Poor solids degradation;
- Nutrients and solids accumulate in bottom of lagoon, which lead to reducing useable volume of lagoon;
- Bacteria wash out.

2- Plug flow digester:

The plug flow digester can be a horizontal or vertical reactor. Usually horizontal digester consists of rectangular tank that are half buried with a hard or flexible membrane cover installed to collect the biogas produced (Fig. 2.27). The feedstock needs to be relatively thick (contains 8 – 12 % of DM) to ensure that feedstock movement maintains the plug flow effect. These digesters are generally not mechanically mixed. Feedstock enters at one end, pushing older substrate forward until it exits. Some systems will re-circulate substrate from the end of tank to inoculate the new material entering and speed up the degradation process. The residence time of substrate (HRT) from 20 to 40 days (**Dennis and Burke, 2001; Anaerobic Digester, 2003; Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

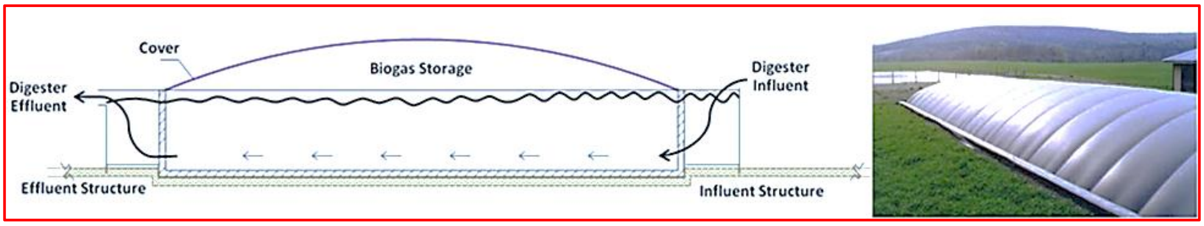

Fig. 2.27: Plug flow digester (as *cited in* **Anaerobic Digester, 2003**)

Main components:

- Mixing tank;
- Digester equipped with heat exchanger and biogas recovery system;
- Effluent storage structure;
- Biogas utilization system.

Advantages:

- Inexpensive;
- Simple to install and operate;
- Fit for livestock manure digestion;
- Works well with scrape systems (systems of manure collection from Corrals);
- Produces high quality fertilizers.

Disadvantages:

- Feedstock must contains more than 8 % of DM;
- Susceptible to contaminants (can't be used with sand bedding);
- Poor mixing of feedstock;
- Poor yield of biogas;
- Nutrients and solids accumulate in bottom of digester, which lead to reducing useable volume of digester;
- Poor solids degradation;
- Membrane-top subject to weather (wind and snow);
- Bacteria wash out.

3- Complete mix digester:

A complete mix organic digester is also known as a completely stirred tank reactor (CSTR, Fig. 2.28). A single (one-stage) CSTR is the most common on-farm digester type with continuous feeding of manure and / or energy crops (*e.g.* maize and / or grass silage). The biogas plant with CSTR technology may also be two- or multi-stages. CSTR usually vertical circular tanks with hard or flexible membrane cover that store biogas. Tanks can be designed in a vertical (top mounted mixer) or flat (side mixers) configuration. CSTR are always mechanically stirred. The fresh feedstock enters the tank and is immediately mixed with the existing, partially digested material. Biogas production proceeds without any interruption from the loading and unloading of the waste material. To optimize the digestion process of the anaerobic bacteria, the digester should be kept at a constant temperature. Typically, a portion of the biogas generated is used to heat the contents of the digester, or the coolant from a biogas-powered generator is returned to a heat exchanger inside the digester tank. The residence time of substrate (HRT) from 20 to 80 days (**Institut für Energetik und Umwelt *et al.*, 2006; Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008 and Rapport *et al.*, 2008**).

Fig. 2.28: Complete mix digester (as *cited in* **Lfu, 2007**)

Main components:

- Mixing tank;
- Digester equipped with mixing, heating and biogas recovery systems;
- Effluent storage system;
- Biogas utilization system.

Advantages:

- Efficient;
- Can digest different feedstocks contains different levels of dry matter;
- Can digest energy crops and by-products with animal manure;

- Good mixing of feedstocks;
- Good solid degradation;
- Can be used with either flush or scrape systems;
- Works well with flush and scrape systems (systems of manure collection from Corrals);
- The manure tanks, which already exist in farms could be converted to biogas digesters by equip them with isolation, stirring and heating systems which leading to construct cheap digester of biogas.

Disadvantages:

- Relatively expensive;
- No guarantee on how much time the material remains in the tank (HRT);
- Requires mechanical mixing system;
- Bacteria wash out.

4- Fixed film digester:

A fixed film digester (Fig. 2.29) also called attached growth digesters or anaerobic filters. Fixed film digester usually consists of a column packed with media, such as wood chips or small plastic rings. Methane-forming microorganisms grow on the media called a bio-film. Usually, effluent is recycled to maintain a constant upward flow. A solids separator is needed to remove particles from the manure before feeding the digester. Efficiency of this system depends on the efficiency of the solids separator; therefore, influent manure concentration should be adjusted to maximize separator performance, (usually, 1 to 5 % total solids concentration of influent manure). The residence time of substrate (HRT) from 1 to 20 days (**Dennis and Burke, 2001; Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007 and EXTENSION, 2012**).

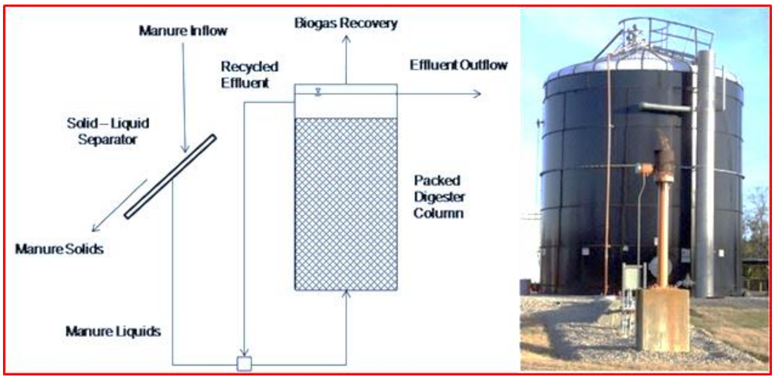

Fig. 2.29: Fixed film digester (as *cited in* **EXTENSION, 2012**)

Main components:

- Solids separator;
- Influent recycling pumps;
- Digester system;
- Biogas utilization system.

Advantages:

- Efficient;
- Good solid degradation;
- Works with dilute feedstock;
- Low HRT (< 20 days);
- Low bacteria wash out.

Disadvantages:

- Expensive;
- Cannot digest feedstock contains high concentration of solids;
- Requires efficient system of solids separation;
- Susceptible to plugging problems by manure solids;
- Some potentials of biogas production are lost due to removing manure solids.

5- Up-flow Anaerobic Sludge Blanket (UASB):

UASB usually, circular tanks with hard tops, but can be found as a rectangle tanks (Fig. 2.30). UASB are mixed by recirculation of influent. UASB have been designed for agri-food waste water treatment. Wastewater is distributed into the tank at appropriately spaced inlets. The wastewater passes upwards through an anaerobic sludge bed where the microorganisms in the sludge come into contact with wastewater substrates. The sludge bed is composed of microorganisms that naturally form granules (pellets) of 0.5 to 2 mm diameter that have a high sedimentation velocity and thus resist wash-out from the system even at high hydraulic loads. The upward motion of released biogas bubbles causes hydraulic turbulence that provides reactor mixing without any mechanical steering. At the top of the reactor, the water phase is separated from sludge solids and gas in a three-phase separator (also known the gas-liquid-solids separator). The three-phase-separator is commonly a gas cap with a settler situated above it. Below the opening of the gas cap, baffles are used to deflect gas to the gas-cap opening. The residence time of substrate (HRT) from 0.5 to 2 days (**Dennis and Burke, 2001; Institut für Energetik und Umwelt *et al.*, 2006; Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007 and Rapport *et al.*, 2008**).

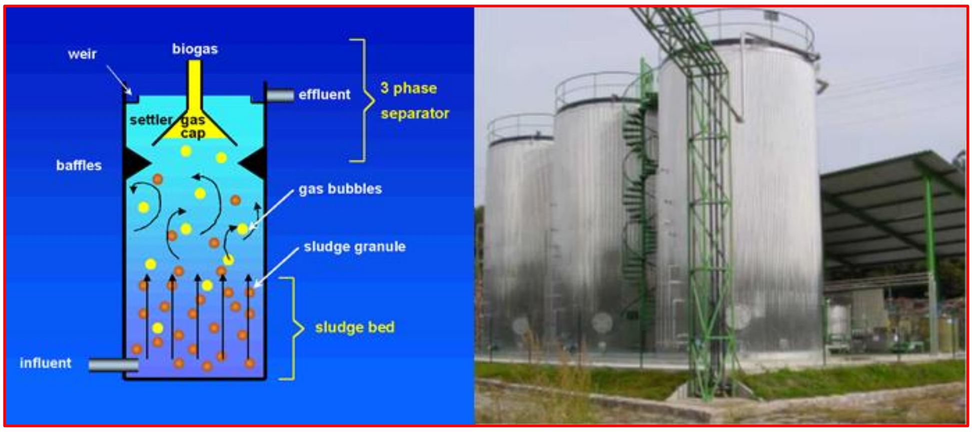

Fig. 2.30: Up-flow Anaerobic Sludge Blanket digester (UASB) (as *cited in* **Anaerobic Granular Sludge Bed Reactor Technology, 2003**)

Main components:

- Mixing tank;
- Digester equipped with heating and biogas recovery systems;
- Effluent storage system;
- Biogas utilization system.

Advantages:

- High efficient;
- Can treat heavy loaded wastewater;
- Good retention of bacteria.

Disadvantages:

- High expensive;
- Not designed to accept high concentrations of suspended solids;
- Complex operating;
- Not widespread for agricultural applications;
- Doesn't digest fats.

2.3.5.2. Dry anaerobic digesters

Dry digesters are systems digest not pumpable feedstock (contains 20 – 40 % dry matter or more) and the digesters equipped with the feeding equipment of solid feedstock. After digestion process the digestate expelled in solid form. Solid digesters may run in batches or continuously (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Rapport *et al.*, 2008 and Kirchmeyr *et al.*, 2009**).

A- Batch systems:

Batch operation is usually used for raw materials with high DM (TS) content, such as solid manure and silage. A garage type is the most common batch reactor (Fig. 2.31). It is filled with a mixture of new feedstock and digestate (for give inoculum) by using *e.g.* a front loader and then closed for biogas producing under airtight conditions. Due to the stirring of feedstock inside the digester is unavailable, leachate is collected via chamber drain and sprayed back on top of the pile to provide a mixing or inoculating effect. Fermentation occurs at mesophilic temperatures at 34 – 37 °C, which are regulated through heated floors and walls. Finally opened and emptied just to start a new cycle again with new feedstock. As the biogas production thus varies depending on the stage of the operational cycle, it is usual to have at least three parallel batches in different stages of operation: one being filled, one in biogas producing phase and one being emptied. The residence time of substrate (HRT) from 20 to 30 days (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Rapport *et al.*, 2008; ZORG, 2012**).

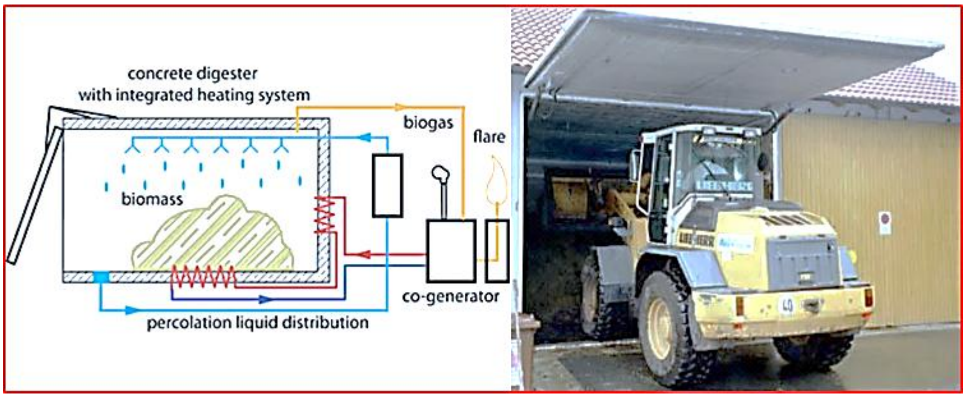

Fig. 2.31: Garage-type batch digester, loaded by loader (as *cited in* **ZORG, 2012**)

Main components:

- Digester equipped with a system of draining, recycling and spraying of leachate, heating and biogas recovery systems;
- digestate storage system;
- Biogas utilization system.

Advantages:

- Efficient;
- Can digest dry feedstocks contains high levels of dry matter;
- Can digest energy crops and by-products with animal manure;
- Good solid degradation;
- No wash out of bacteria.

Disadvantages:

- High expensive;
- Uneven gas production and lack of stability in the microbial population;
- Need to 3 digesters -at least- works in parallel (at different stages of digestion) to overcome the volatility of biogas production;
- No guarantee on how much time the material remains in the tank (HRT).

B- Continuous systems:

In continuous dry digesters, feedstock is constantly fed into the digester. The substrate moves through the digester either mechanically or by the pressure of the newly feed substrate, which pushing out the digested material. Unlike batch-type digesters, continuous digesters produce biogas without interruption and biogas production is constant and predictable. Continuous digesters could be vertical or horizontal and could be single or multiple tanks systems. Completely mixed digesters are typically vertical digesters while plug-flow digesters are horizontal (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007 and Al Seadi *et al.*, 2008**).

1- Vertical dry digesters:

Vertical cylindrical digester (Fig. 2.32) is fed from the top with chopped feedstock and where digested digestate are removed from the bottom. Fresh feedstock material is processed into small pieces and mixed with digested material and fed to the digester using a screw feeding system to ensure bacterial inoculation at the top of the digester. There is a vertical plug flow from the top to the bottom. A screw removes material from the bottom. The residence time of substrate (HRT) from 20 to 40 days (**Electrigaz Technologies Inc., 2007; Lfu, 2007; Zaher *et al.*, 2007; Al Seadi *et al.*, 2008; Rapport *et al.*, 2008 and Ontario, 2011**).

Fig. 2.32: Vertical dry digester (as *cited in* **Zaher *et al.*, 2007**)

Main components:

- Digester equipped with feeding equipment of solid feedstock, heating and biogas recovery systems;
- digestate storage system;
- Biogas utilization system.

Advantages:

- Efficient;
- Can digest dry feedstocks contains high levels of dry matter;

- Digester has a relatively small size compared with wet digesters systems and produce high biogas yield;
- Alternative to traditional production method of smelly composting, and producing high quality compost.

Disadvantages:

- High expensive;
- Feedstock needs to size reduction by chopping for accelerating digestion;
- Has complex mechanical structure and maintenance;
- No mixing of substrate lead to reduction the potentials of biogas yield;
- Poor Solids degradation.

2- Horizontal dry digesters:

Horizontal digesters (Fig. 2.33) consist of horizontal cylindrical shape and equipped with a heating system, gas dome, manure pipes and stirring system. This type of digesters is usually manufactured in one piece of stainless steel, so that they are limited in size and volume. The standard type for small scale digester is a horizontal steel tank with volume from 50 to 150 m^3, which uses as a main digester for small biogas plants or as pre-digester for larger plants, for increase the digestion efficiency of main digester. There are also alternative digesters made of concrete, with volume up to 1000 m^3. Horizontal digesters can also run in parallel (Fig. 2.34), in order to produce more biogas yield. Horizontal continuous flow digesters are usually used for dry feedstock like chicken manure, grass, maize silage or manure with a high straw content. The residence time of substrate (HRT) from 20 to 40 days (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Rapport *et al.*, 2008 and Nordic Folkecenter, 2010**).

Fig. 2.33: Horizontal dry digester (as *cited in* **Nordic Folkecenter, 2010**)

Fig. 2.34: Horizontal dry digesters run in parallel (as *cited in* **Nordic Folkecenter, 2010**)

Main components:

- Digester equipped with feeding equipment of solid feedstock, stirring, heating and biogas recovery systems;
- digestate storage system;
- Biogas utilization system.

Advantages:

- Efficient;
- Good mixing of feedstocks;
- Can digest dry feedstocks contains high levels of dry matter;
- Digester has a small size compared with wet digesters systems and produce high biogas yield;
- Alternative to traditional production method of smelly composting, and producing high quality compost;
- Good Solids degradation.

Disadvantages:

- High expensive;
- Feedstock needs to size reduction by chopping for accelerating digestion;
- Has complex mechanical structure and maintenance;
- Has a limited productivity.

2.3.6. Stirring systems

The indirect stirring could occur by feeding of fresh feedstock and the subsequent thermal convection streams as well as by the up-flow of gas bubbles. As indirect stirring is not sufficient for optimal operation of the digester, active stirring must be applied by using mechanical, hydraulic or pneumatic equipment. Up to 90 % of biogas plants use mechanical stirring equipment for increasing the digestion efficiency and biogas yield (**Sasse, 1988; Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

The substrates inside the digester must be stirred several times per day for mixing the new feedstock with the existing substrate inside the digester. Moreover, stirring prevents formation the layers of floating sediments, facilitates the up-flow of gas bubbles and homogeneity distribution of heat and nutrients through the whole mass of substrate (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

2.3.6.1. Mechanical stirring

According to rotation speed, mechanical stirrers can be fast, medium and slow running stirrers. Submersible motor propeller stirrers (Fig. 2.35) are frequently used in vertical digesters. They are completely immersed in the feedstock and usually have two or three wings, geometrically optimized propellers. Paddle stirrers have a vertical, horizontal or diagonal axis (Figs. 2.36, 2.37 & 2.38). The motor is positioned outside the digester. Junctions, where the shaft passes the digester ceiling, membrane roof or the digester wall, have to be tight. (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

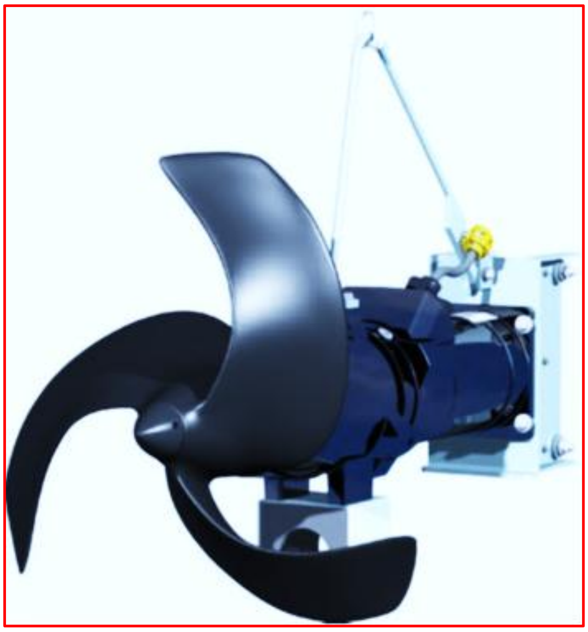

Fig. 2.35: Submersible motor propeller stirrer

(as *cited in* **Wilo Mixers, 2011**)

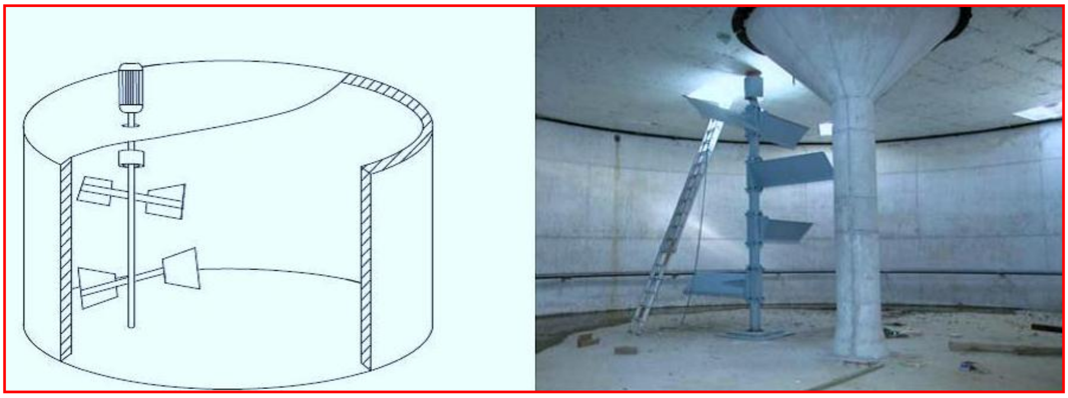

Fig. 2.36: Vertical hanging paddle stirrers (as *cited in* **Lfu, 2007**)

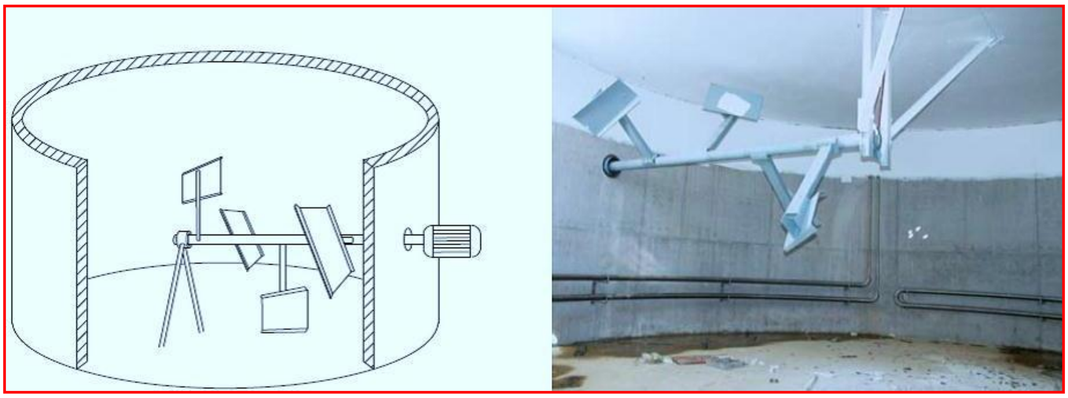

Fig. 2.37: Horizontal hanging paddle stirrers (as *cited in* **Lfu, 2007**)

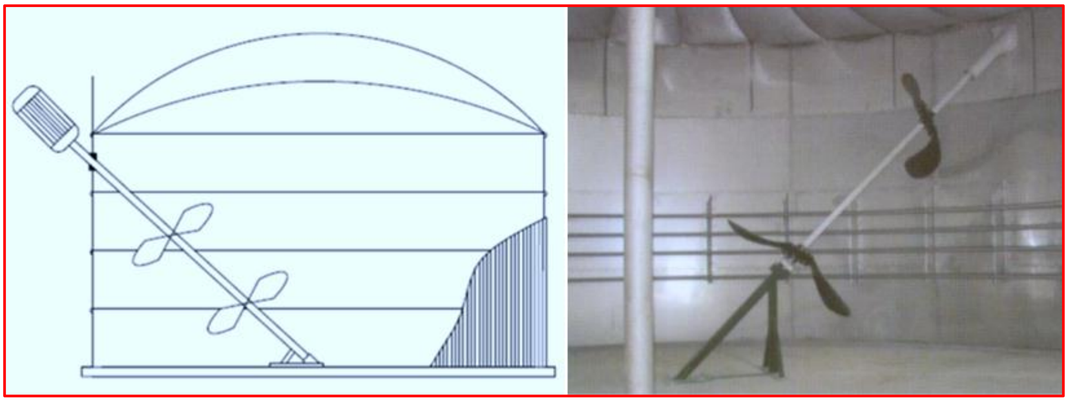

Fig. 2.38: diagonal paddle stirrers (as *cited in* **Lfu, 2007**)

2.3.6.2. Hydraulic stirring

Hydraulic stirring system (Fig. 2.39) works by press the feedstock by pumps through horizontal or additional vertical vents into the digester. Hydraulically stirred systems have the advantage that the mechanical parts of the stirrers are placed outside the digester, subject to lower wear and can be easily maintained. Hydraulic stirring is appropriate for destruction of floating layers of sediments (**Wellinger, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

2.3.6.3. Pneumatic stirring

Pneumatic stirring system (Fig. 2.40) uses the produced biogas, by injection the biogas from the bottom of the digester through the mass of the feedstock. The bubbles of rising gas cause a vertical movement and stir the feedstock. Pneumatic stirring not frequently used in agricultural biogas plants, as the technology is not appropriate for destruction of floating layers of sediments (**Wellinger, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007 and Al Seadi *et al.*, 2008**).

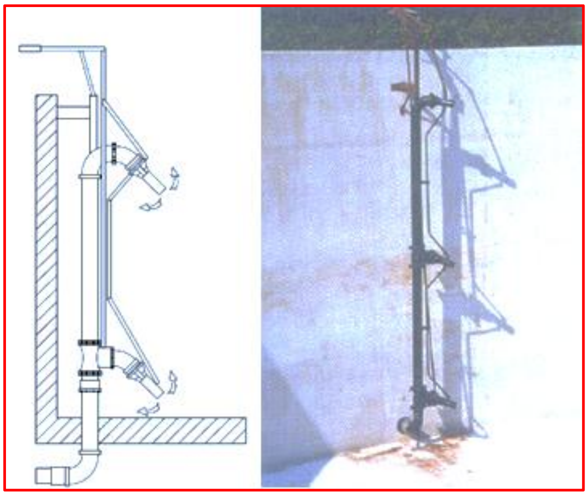

Fig. 2.39: Hydraulic stirring system (as *cited in* **Lfu, 2007**)

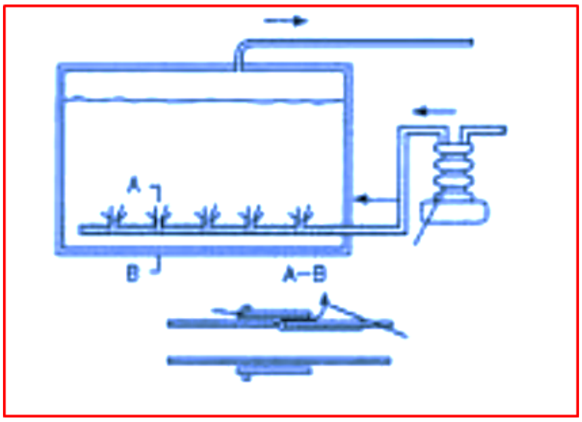

Fig. 2.40: Pneumatic stirring system (as *cited in* **Wellinger, 1999**)

2.3.7. Biogas storage

A biogas storage system essentially required to provides a constant gas pressure to the CHP unit. Biogas is typically generated at unstable rate during the anaerobic digestion process and the fluctuation of biogas production is increasing when inhomogeneous feedstocks are digesting such as agricultural residues and food wastes. Correct selection and dimensioning of biogas storage facility brings substantial contribution to the efficiency, reliability and safety of the biogas plant while ensuring constant supply of biogas and minimizing biogas losses (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008 and ZORG, 2012**).

The use of digesters is integrates with the use of innovative or non-traditional biogas storage options. The simplest biogas storage is established on top of digesters, using a gas tight membrane (Fig. 2.41), which consists of one or two membranes (the external membrane forms the outer shape and the internal membrane seals the digester gas-tight). For safety reasons, biogas holders must be equipped with safety valves (under-pressure and over-pressure, Fig. 2.42) to avoid unsafe biogas pressure levels (negative or positive) into digester. Usually, a capacity from one to two days is recommended for use the biogas tight membranes (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; SATTLER AG & Ceno Membrane Technology GmbH, 2010 and ZORG, 2012**).

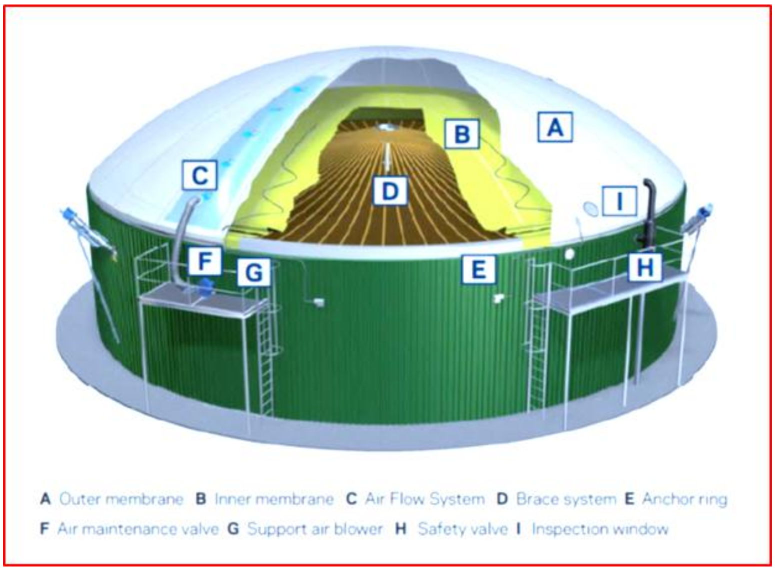

Fig. 2.41: Biogas tight membranes (as *cited in* **SATTLER AG & Ceno Membrane Technology GmbH, 2010**)

Fig. 2.42: Safety pressure valves (as *cited in* **ZORG, 2012**)

2.3.7.1. Low pressure tanks

Low pressure storage facilities of biogas are most common use. They have a pressure range from 0.05 to 50 mbar and made of special membranes, which must meet a number of safety requirements. The membrane tanks are installed on the top of the digesters as a covers or as external gas holders as gas domes. External low-pressure tanks can be designed in the shape of membrane cushions (Fig. 2.43) or gas balloons (Fig. 2.44). (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; SATTLER AG & Ceno Membrane Technology GmbH, 2010 and ZORG, 2012**).

Fig. 2.43: Gas cushion tank (as *cited in* **SATTLER AG & Ceno Membrane Technology GmbH, 2010**)

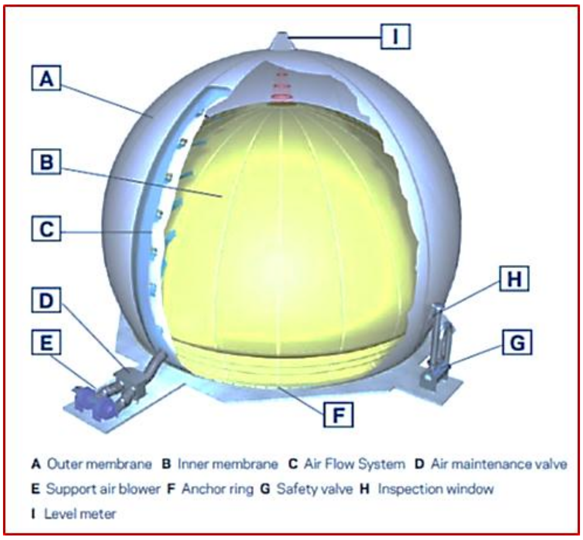

Fig. 2.44: Gas balloon tank (as *cited in* **SATTLER AG & Ceno Membrane Technology GmbH, 2010**)

2.3.7.2. Medium and high pressure tanks

Biogas can also be stored in medium and high pressure tanks made of steel (Fig. 2.45) at pressures between 5 and 250 bar. These kinds of storage types have high operation costs and high energy consumption. (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; SATTLER AG & Ceno Membrane Technology GmbH, 2010 and ZORG, 2012**).

Fig. 2.45: High pressure tank of biogas (as *cited in* **ZORG, 2012**)

2.3.8. Digestate storage

After the digestion process is complete, the digestate is dewatered and uses as fertilizer, it is transported away from the biogas plant, through pipelines or with special vacuum tankers, and temporarily stored in storage tanks placed *e.g*. out in the fields, where the digestate is applied. The total capacity of these tanks must be enough to store the production of digestate for several months. Digestate can be stored in concrete tanks or in lagoon ponds, covered by natural or artificial floating layers or by membrane covers (Fig 2.46) (**Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Lukehurst *et al.*, 2010 and Frandsen, 2011**).

Fig. 2.46: Covered digestate storage tank (as *cited in* **Lukehurst *et al.*, 2010**)

2.4. Biogas characteristics

The characteristics of biogas vary depending on feedstock types, digestion systems, temperature of digestion, hydraulic retention time etc. Table (2.8) illustrated some average biogas composition values. Considering biogas with the standard methane content of 60 %, the caloric value (heating value) is 6 kWh / m³ (21 MJ / m³) while the calorific value of natural gas contains 99 % methane is 9 kWh / m³, on the other hand one m^3 of biogas will produce approximately 1.7 kWh of electricity and 2 kWh of heat from CHP unit has power conversion efficiency 60 %. The biogas density is 1.265 kg / m³ similar to the air (1.29 kg / m³). Theoretical methane production is varies according to their biochemical composition, as illustrated in Table (2.9) (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Genesis Projects Corp, 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009 and Frandsen *et al.* ,2011**).

Table 2.8: Composition of raw biogas (author elaboration *cited in* **Electrigaz Technologies Inc., 2007**)

Compound	Chemical symbol	Content (Vol. - %)
Methane	CH_4	50 -75
Carbon dioxide	CO_2	20 - 45
Water vapor	H_2O	2 (20°C) - 7 (40°C)
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulphide	H_2S	<1

Table 2.9: Theoretical gas production (author elaboration *cited in* **Al Seadi *et al.,* 2008**)

Substrate	Liter of gas / kg TS	CH_4 (%)	CO_2 (%)
Raw protein	700	70 to 71	29 to 30
Raw fat	1200 to 1250	67 to 68	32 to 33
Carbohydrates	790 to 800	50	50

The methane production from the AD depends on the source of substrate, as illustrated in Table (2.10).

Table 2.10: Methane production from different feedstock materials (author elaboration *cited in* **Al Seadi *et al.,* 2008**)

Feedstock	Biogas yield (m^3 / ton of FF[8])	Methane content (%)
Liquid cattle manure	25	60
Liquid pig manure	28	65
Distillers grains with soluble	40	61
Cattle manure	45	60
Pig manure	60	60
Poultry manure	80	60
Beet	88	53
Organic waste	100	61
Sweet sorghum	108	54
Forage beet	111	51
Grass silage	172	54
Corn silage	202	52

2.5. Biogas utilization

Utilizations of biogas are varying according to the nature of the biogas source and the local demand; different uses of biogas are illustrated in Table (2.11) (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

[8] FF=fresh feedstock

Table 2.11: Different technologies for utilization and upgrading of biogas (author elaboration *cited in* **Electrigaz Technologies Inc., 2007 and Frandsen *et al.*, 2011**)

Utilization of biogas	Technologies	Cost	Efficiency	Complexity	Reliability
Heat production only	Biogas burners and boilers	Low	Medium	Low	High
Power production only	Internal combustion	Medium	Medium	Medium	High
	Gas turbines	High	Medium	High	Medium
	Fuel cells	Very high	High	High	Low
Combined heat and power generation (CHP)	Otto and diesel engines adapted for biogas	Medium	High	Medium	High
	Gas turbines and micro turbines	High	High	High	Medium
	Stirling motors	Medium	High	High	Medium
	Organic Rankine cycle (ORC)	High	High	High	Medium
Biogas upgrading	Pressure Swing Adsorption (PSA)	Very high	High	High	Variable
	Absorption: Water scrubbing Organic physical scrubbing Chemical scrubbing	Very high	High	High	Variable
	Membrane technology	Very high	High	High	Variable
	Cryoprocesses	Very high	High	High	Variable
	In situ enrichment	Very high	High	High	Variable
	Ecological lung	Very high	High	High	Variable

2.5.1. Biogas preparation before utilization

Biogas is not absolutely pure, but contains impurities such as water droplets, dust, mud and traces of unwanted gases (such as carbon dioxide (CO_2), hydrogen sulphide (H_2S), and ammonia (NH_3), which cause corrosion of metals in the presence of water and high temperature). All this contaminants have to be removed, depending on the utilizations of the biogas. Solid particles in the biogas and sometimes oil-like components are filtered out of the biogas by the usual dust filters. Sludge and foam components are separated in cyclones. The separation can be improved by injecting water into the biogas before the cyclone, process water can be used. For removing the traces of unwanted gases, scrubbing, adsorption, absorption, and drying are applied. In the case of biogas is just burning, *e.g.*, in a gas burners, no necessity exist for the purification of the biogas but the exhaust air after burning might to be decontaminated (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Kirchmeyr *et al.*, 2009; Frandsen *et al.*,2011 and ZORG, 2012**).

2.5.2. Direct combustion

The simplest way of utilizing biogas is direct combustion in burners or boilers (Fig. 2.47), to produce heat. This technology has low investment and maintenance costs and is well-known and reliable. For small scale biogas plants located at a site with a high heat demand, it is probably the best alternative, at least in countries with rather low price for electricity produced with biogas. The heat demand at a farm during summer can, as a monthly average, be about 20 % compared with a winter month. In boilers, the requirements for biogas quality are low but it is recommended to reduce the level of hydrogen sulphide content below 1.00 ppm, which allows the exhaust gases to maintain a dew point around 150 °C (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

Fig. 2.47: Biogas burner for steam boiler (as *cited in* **Electrigaz Technologies Inc., 2007**)

2.5.3. Internal combustion

One of the most common technologies of power generation is internal combustion engines, which can be used to burn biogas for generate electricity that can be sold to the power grid. Engines are available in sizes from a few kilowatts up to several megawatts. Gas engines can either be Otto-engines (spark ignition) or dual fuel engines. Otto generators (Fig. 2.48) are equipped with normal ignition systems and a gas / air mixing system that provides a combustible mixture to the engine. Dual fuel generators (Fig. 2.49) with injection of diesel (10 % and up) used as a pilot fuel to ignite biogas during combustion. Internal combustion engines are very popular in small scales because they have good electric efficiencies up to 40 % (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008 and Frandsen *et al.*, 2011**).

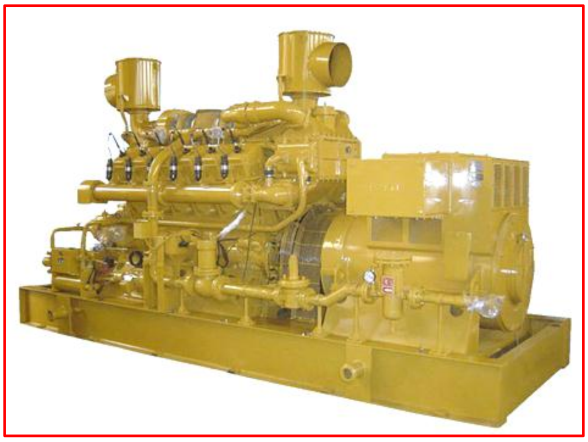

Fig. 2.48: Biogas Otto-generator (as *cited in* **Alibaba.com, 2012**)

Fig. 2.49: Dual fuel-generator (as *cited in* **DIRECTINDUSTRY, 2012**)

2.5.4. Gas turbines

Modern gas turbines (Figs. 2.50 and 2.51) are derivatives from aviation gas turbine, which exhaust gases are directly expanded through the turbine and the plant size is often above 800 kWh_{el}. The fact that the exhaust gases expand directly in the turbine wheel, poses strict fuel purity requirements. In recent years also small scale engines, so called micro-turbines in the range of 25 to 200 kWh_{el} have been successfully introduced in biogas applications. They have efficiencies comparable to small Otto-engines with low emissions and allow recovery of low pressure steam which is interesting for industrial applications (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

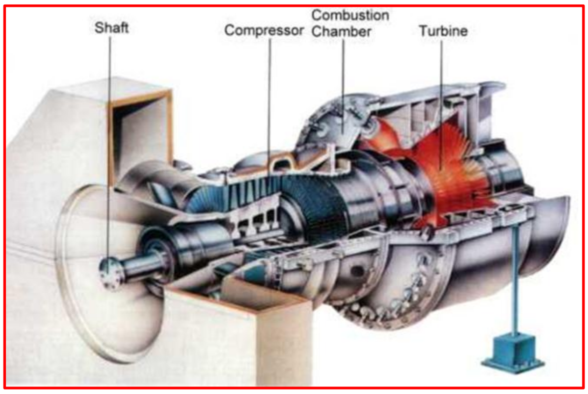

Fig. 2.50: Gas turbines (as *cited in* **Gas Turbines, 2008**)

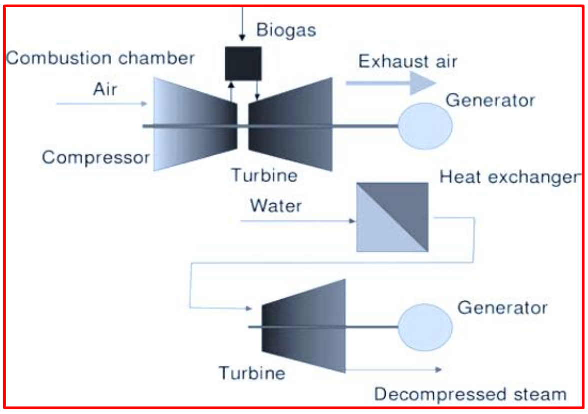

Fig. 2.51: Gas turbine process with heat recovery in a steam turbine downstream (as *cited in* **ZORG, 2012**)

2.5.5. Fuel cells

The fuel cells (Fig. 2.52) are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The basic physical structure (building block) of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on both sides with continuously fed of fuel (Hydrogen) to the anode and air (Oxygen) to the cathode. Fuel cells have a potential to become the small scale power plant of the future. Nevertheless, widespread commercial use is yet to be achieved. Fuel cells have a potential to reach very high efficiencies (more than 60 %) and low emissions. Fuel cells still considered in the realm of research and development. Currently, fuel cells do not offer the reliability necessary to ensure economic feasibility of biogas projects. It will take many years before the fuel cell can surpass the internal combustion engine as a reliable biogas energy conversion technology (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 201 and ZORG, 2012**).

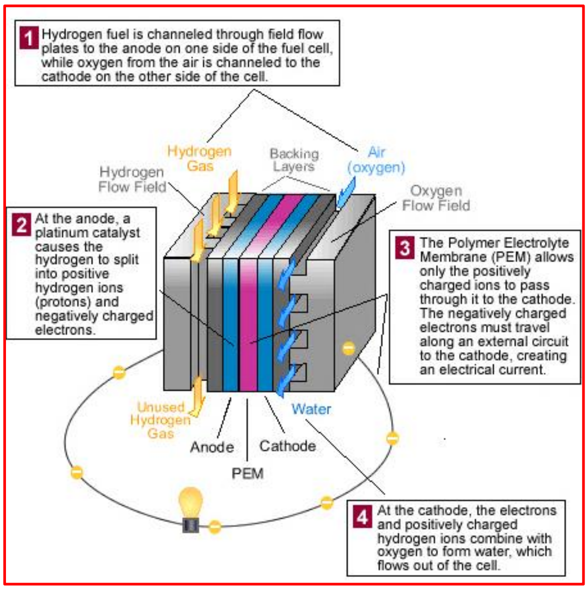

Fig. 2.52: Simplified scheme of a fuel cell (as *cited in* **www.fueleconomy.gov., 2012**)

2.5.6. Combined heat and power (CHP)

CHP generation is a common utilization of biogas in many countries with a developed biogas sector, and it is considered a very efficient of biogas utilization for energy production. The most common types of CHP plants are block type thermal power plants (BTTP) with combustion motors that are coupled to a generator. The total efficiency of CHP unit is considered the sum of the electrical and thermal efficiencies, is within the range 85 - 90 % with modern CHPs and only 10 - 15 % of the energy of the biogas is wasted. But the electrical efficiency (maximum 40 %) is still very low (from 1 m^3 biogas only 2.4 KWh, electric current can be produced). Most common CHP plants are Otto or ordinary diesel engines using biogas as fuel. Other technologies of CHP are gas turbines, Stirling motors and organic Rankine cycle (ORC) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

2.5.6.1. Gas-Otto engines

Gas-Otto motors (Fig. 2.53) are developed specifically for using biogas according to the Otto principle. In gas-Otto engine air and fuel are mixed before entering engine cylinders where the mixture is fired by spark plugs. Gas-Otto motors require biogas with minimum 45 % methane content. Small engines, up to 100 kWh_{el} are usually Otto engines. Gas-Otto engines can be operated with biogas or natural gas. Usually with diesel engines 35 - 45 % of the energy content of the fuel can be converted into electricity, depending on the size of the unit, in comparison with similar size the efficiency of Otto-engines is in general lower, about 27 - 38 % (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

Fig. 2.53: CHP unit equipped with gas-Otto engine (as *cited in* **BSRIA, 2010**)

2.5.6.2. Pilot-injection gas engines

The pilot injection engine (also called pilot injection natural gas engine, PINGE, or dual fuel engine) is based on the diesel engine principle (Fig. 2.54). In diesel engines converted to biogas the fuel-air mixing is basically similar to Otto-engines. Since biogas does ignite by the cylinder compression unlike diesel fuel, a small amount of diesel is used to ignite the mixture, usually; the oil injection is 2 - 5 % during normal conditions. Different uses of heat and power produced from on-farm CHP unit illustrated in Table (2.12) (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

Fig. 2.54: CHP unit equipped with pilot Injection gas engine

(as *cited in* **HAZEN AND SAWYER, 2012**)

Table 2.12: Different uses of heat and power produced from on-farm CHP unit (author elaboration *cited in* **Kirchmeyr *et al.*, 2009**)

Heat	Electricity
• Usually, 1 / 3 of the heat is used for heating the digesters (process heat); • 2 / 3 can be used for external needs; • Heat transport through district heating system; • Alternative: Micro gas with CHP generation at the heatsink site; • Power-heat-cooling coupling.	• Produced electricity can be used as process energy and sold to grid; • About 7 - 10 % of the produced electricity from biogas, are used for biogas production process; • Due to the height prices of electricity, after consuming of the process electricity and meets the on-farm requirements of electricity, all surplus of the electrical production from biogas plant is sold to electrical grid.

2.5.6.3. Gas turbines and micro turbines

In a gas turbine compressed fuel-air mixture burns continuously and the velocity of the hot gases rotate a turbine, which is connected to a generator and producing electricity. Electrical efficiency is usually somewhat lower than in Otto or diesel engines. In small units, micro turbines (Fig. 2.55), hot exhaust gases can be used for heating and in big units exhaust gases can generate steam which can rotate a turbine generating power. The electric capacity of biogas micro turbines is typically below 200 kWh_{el}. The cost of biogas micro-turbines is high and the research work in this area is therefore aiming cost reduction for future models (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

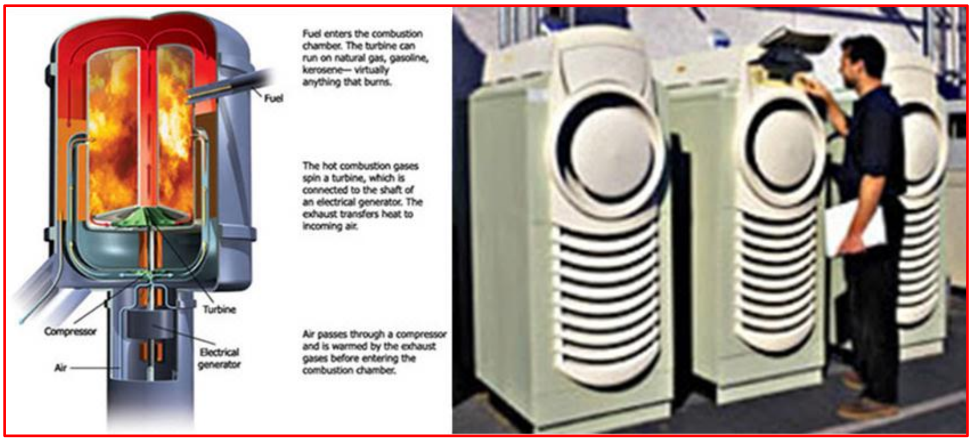

Fig. 2.55: Gas micro turbine (as *cited in* **WBDC, 2012**)

2.5.6.4. Stirling motors

The Stirling motor (Fig. 2.56) operates with external combustion. The combustion takes place outside the engine and combustion products do not come into contact with the internal parts of the engine, almost any kind of fuel can be used as heat source. Based on the principle that changes of gases temperature leads to changes of gases pressure and volume. The pistons of the engine are moved by gas expansion caused by heat injection from an external energy source. The required heat can be provided from various sources such as a gas burner, running on biogas. In comparison to internal combustion engine, Stirling engine is quieter, and more reliable with less need for maintenance. The electrical efficiency of the Stirling engine is of 24-28 %, which is lower than Gas-Otto engines (**Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Frandsen *et al.*, 2011 and ZORG, 2012**).

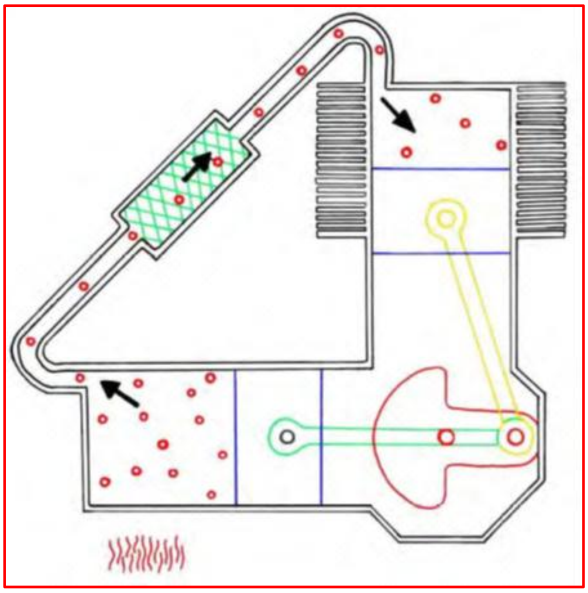

Fig. 2.56: Schematic construction of an alpha stirling containing two pistons, one hot, one cold and a regenerator in the connecting pipe (as *cited in* **Frandsen *et al.*, 2011**)

2.5.6.5. Organic Rankine cycle (ORC)

The Organic Rankine cycle (Fig. 2.57) works like steam turbine by using an organic matter instead of water as working fluid. ORC suits the low temperatures and small scales. The heat source can be a motor's exhaust pipe, waste heat from an industrial processes or the burning of biogas or other types of fuels. The working organic fluid is expanded in a turbine in the form of overheated vapor under high pressure. The pressure then drops and power is delivered to the high speed generator. The expanded vapor still has usable heat that is supplied to the cold working fluid in the recuperator (heat exchanger). Afterwards the vapor is condensed in the condenser and the fluid is pressurized to the required high pressure. The liquid is then warmed in the already mentioned recuperator and then vaporized and overheated in the boiler. The boiler is heated by the external heat that the ORC converts to electricity. For biogas plants it can be difficult to get full advantage of heat produced all year around. Recovering the waste heat in such cases can increase the electricity generation further. Use of external combustion engines like Stirling motors or ORC are ways to do it (**Spliethoff and Schuster 2006; Lfu, 2007 and Frandsen *et al.*, 2011**).

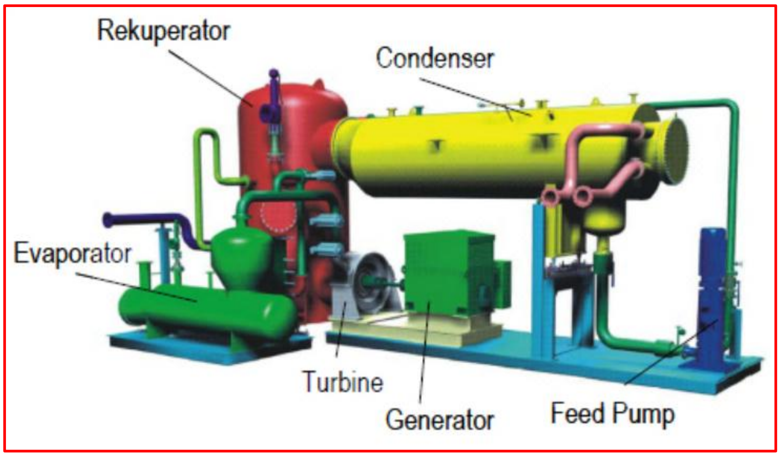

Fig. 2.57: ORC unit (as *cited in* **Spliethoff and Schuster 2006**)

2.5.7. Biogas upgrading (biomethane production)

Biogas must undergo to upgrading process (Fig. 2.58) before injection into the natural gas grid or to utilization as vehicle fuel. Upgrading process aims to remove all contaminants as well as CO_2 and increase the content of methane from usual 50 - 75 % (in biogas) to more than 97 %. Technologies such as pressure swing absorption and water scrubbing are used to remove CO_2 from the biogas stream and converting it to biomethane (upgraded biogas). Biogas upgrading technologies are becoming increasingly attractive as it does not have the heat losses and emission issues related to the internal combustion engine and electrical energy generation. Moreover, the final product is identical to natural gas and can be transported efficiently using the existing natural gas grid. Unlike natural gas, which contributes greenhouse gas emissions to the atmosphere, the combustion of upgraded biogas actually reduces greenhouse gas emissions to the atmosphere by displacing natural gas (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009 and Frandsen *et al.*, 2011**).

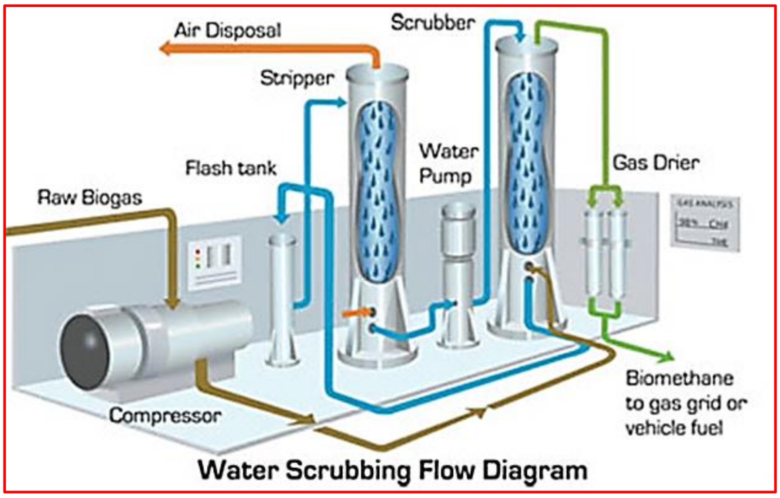

Fig. 2.58: Biogas upgrading unit (as *cited in* **FLOTECH, 2010**)

2.5.7.1. Biogas as vehicle fuel

Utilization of biogas in the transport sector is a technology with great potentials and with important socio-economic benefits. Upgraded biogas (biomethane) is considered to have the highest potentials as vehicle fuel, even when compared to other biofuels. Fig. (2.59) illustrated a comparison between transport biofuels, in terms of covered distance by an automobile, when running on the respective biofuel, produced on energy crops cultivated on one hectare arable land (**Electrigaz Technologies Inc., 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009 and Frandsen *et al.*, 2011**).

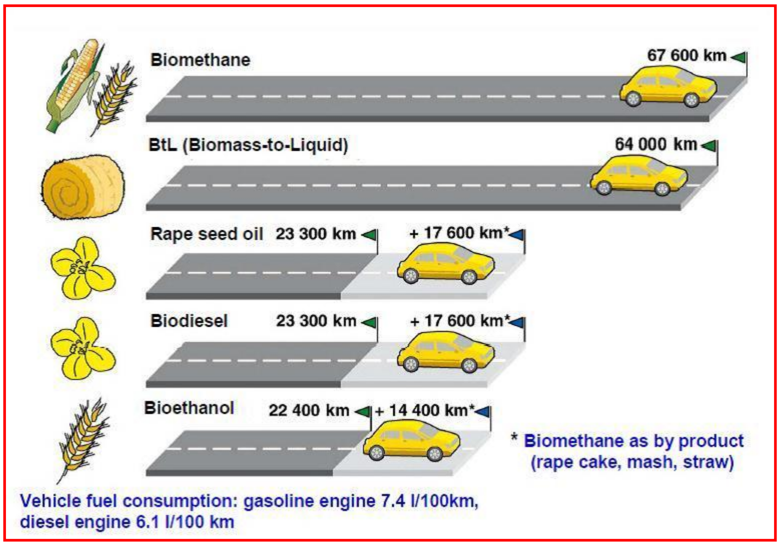

Fig. 2.59: Biofuels in comparison: Range of a personal car, running on biofuels produced on feedstock / energy crops from one hectare arable land (as *cited in* **Fnr, 2008** *cited in* **Al Seadi *et al.*, 2008**)

2.5.7.2. Biomethane for grid injection

Upgraded biogas (biomethane) can be injected and distributed through the natural gas grid, after it has been compressed to the pipeline pressure. In many EU countries, the access to the gas grid is guaranteed for all biogas suppliers (**Electrigaz Technologies Inc., 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009 and Frandsen *et al.*, 2011**).

2.6. Economical considerations to establish on-farm biogas system

In the anaerobic digestion process the biogas production process and subsequent cogeneration process of thermal and electrical energy are undoubtedly the decisive moments of the entire process. Proper management of these processes is crucial for the economic viability of this industry. The estimated costs of construction and management of on-farm biogas system must be particularly careful considering the many variables that effect on the correct functioning specially for selection of appropriate technology applying (**Karellas *et al.*, 2010 and Ragazzoni, 2011**).

2.6.1. Fixed costs (costs of construction)

Fixed costs (see Table 2.13) of on-farm biogas system depending on the characteristics of technology applied of digestion process (from simple to sophisticated technology equipped with measurements and controlling systems), size (dimensions) of the biogas system (the cost of energy unit produced decreasing with increasing power capacity of installed CHP unit) and the feedstock materials used for biogas production (silage of energy crops, manure slurry, agricultural by-product and residues and agro-industrial waste, etc.) (**Karellas *et al.*, 2010 and Ragazzoni, 2011**).

Recent researches results indicate to fixed costs fluctuate in relation to the above-mentioned variables, between 3000 and 7000 euro / kW_{el} of on-farm CHP unit capacity. The range of these values seems rather large, but also confirmed by surveys applied at samples of new installed on-farm biogas plants (**Karellas *et al.*, 2010 and Ragazzoni, 2011**).

According to the power capacity of installed CHP unit, the on-farm biogas plants could be classified into three categories:

- Small scale < 250 kWh_{el};
- Medium scale 250 - 500 kWh_{el};
- Large scale > 500 kWh_{el}.

Table 2.13: Estimated fixed costs of establish on-farm biogas system, based on installed electrical capacity of on-farm CHP unit (author elaboration *cited in* **Ragazzoni, 2011**)

Components of biogas Plant	< 250 kWh_{el}		250 - 500 kWh_{el}		> 500 kWh_{el}	
	Euro / kW_{el}					
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Concrete constructions	2300	3000	2000	2300	1400	2000
Mechanical and electrical components	2000	2500	1500	2000	1000	1500
CHP unit	1200	1500	1000	1200	600	1000
Total	**5500**	**7000**	**4500**	**5500**	**3000**	**4500**

2.6.2. Variable costs (operating costs)

Variable costs (see Table 2.14) are the costs related to the management and operating of the plant. Generally, for investment at biogas projects the payback period of invested capital is from 6 - 7 years (**Karellas *et al.*, 2010 and Ragazzoni, 2011**).

Table 2.14: Estimated variable costs of operating on-farm biogas system, based on electrical energy generated from on-farm CHP unit (author elaboration *cited in* **Ragazzoni, 2011**)

Expenditure trends	**Minimum (Euro / kWh_{el})**	**Maximum (Euro / kWh_{el})**
Management	0.009	0.010
Repair and periodic maintenance	0.006	0.009
Operating and services	0.020	0.040
Chemical and physical analysis	0.002	0.003
Overheads	0.010	0.012
Total	**0.047**	**0.074**

It should be mention that, according to the Italian law the biogas plant has a power capacity of CHP unit less than 100 kWh_{el} , can be establish without official permit from administrative authorities, while the biogas plant has a power capacity of CHP unit more than 300 kWh_{el} loses the right of obtain subsidies and incentives.

3

MATERIAL AND METHODS

3. MATERIAL AND METHODS

3.1. Material

RAF is a bio-energetic descriptive model integrates with MAD model (**Vitali *et al.*, in press**) to support Integrated Farm Management (IFM). RAF model aimed to enhancing economical, social and environmental sustainability of farm production in terms of energy via converting energy crops and animal manure to biogas and digestate (bio-fertilizers) by using anaerobic digestion (AD) technologies, growing and breeding practices. The user defines farm structure in terms of present crops, livestock, market prices, etc. and RAF model investigates the possibilities of establishing on-farm biogas unit (different anaerobic digestion (AD) technologies proposed for different scales of farms in terms of energy requirements) according to budget and sustainability constraints for reduce the dependence on fossil fuels. The objective function of RAF (Z) is optimizing the total net income of farm (maximizing income and minimizing costs) for whole period which is considered by analysis.

3.1.1. Farm characteristics under study

The farm under study should be has a set of conditions as follows:

- The farm consists of one unit with specific borders to distinguish from the other farms;
- Farm production should be oriented to conventional or organic production (mixing between conventional and organic is not allowed);
- Farm applying integrated co-production of agricultural and livestock products;
- Farm managed by the owner himself without rent, brokers and agents;
- Farm has a potentials for applying and using renewable energy (bioenergy) with conventional energy or replace it;
- The family labor (for free) is not considered;
- Inter-cropping and cultivation of more than one type of crops at the same site is not considered;
- Erosion and soil degradation is not considered;
- Natural areas income and costs are not considered.

3.2. Methods

3.2.1. Linear programming

Linear programming (LP) is a mathematical technique use in computer modeling (simulation) to find the best possible solution in allocating limited resources (energy, machines, materials, money, personnel, space, time, etc.) to achieve maximum profit or minimum cost. However, it is applicable only where all relationships are linear and can accommodate only a limited class of cost functions. For problems involving more complex cost functions, another technique called 'mixed integer modeling' is employed (**Schulze, 1998; Miller, 2007 and Rosenthal, 2012**).

LP is the most commonly applied form of constrained optimization. Constrained optimization is much harder than unconstrained optimization.

The main elements of any constrained optimization problem are:

- Variables (also called decision variables). The values of the variables are not known when you start the problem. The variables usually represent things that you can adjust or control, for example the rates at which manufacture items. The aim is to find values of the variables that provide the best value of the objective function;
- Constraints. These are mathematical expressions that combine the variables to express limits on the possible solution. For example, they may express the idea that the number of workers available to operate a particular machine is limited, or that only a certain amount of feedstock is available per day;
- Variable bounds. Only rarely are the variables in an optimization problem permitted to take on any value from minus infinity to plus infinity. Instead, the variables usually have bounds. For example, zero and 100 might bound the production rate of widgets on a particular machine;
- Objective function. This is a mathematical expression that combines the variables to express your aim. It may represent profit, for example. You will be required to either maximize or minimize the objective function.

In LP, all of the mathematical expressions for the objective function and the constraints are linear. The programming in linear programming is an archaic use of the word "programming" to mean "planning". So you might think of linear programming as "planning with linear models". You might imagine that the restriction to linear models severely limits your ability to model real-word problems, but this isn't so. An amazing range of problems can be modeled using linear programming, everything from airline scheduling to least-cost petroleum processing and distribution. LP is very widely used. For example, IBM estimated that in 1970, 25 % of all scientific computation was devoted to linear programming (**Schulze, 1998; Miller, 2007 and Rosenthal, 2012**).

Linear programming is by far the most widely used method of constrained optimization. The largest optimization problems in the world are LPs having millions of variables and hundreds of thousands of constraints. With recent advances in both solution algorithms and computer power, these large problems can be solved in practical period of time (**Schulze, 1998; Miller, 2007 and Rosenthal, 2012**).

3.2.2. Description of MAD model

MAD (Figs. 3.1 & 3.2) is a bio-economical model aimed to optimize resources of a farm holding (surfaces, livestock, labor, etc.) to approach an objective function (Z) aimed to maximize net income of farm for whole period which is considered by analysis (see mathematical programming, simplex method) (**Vitali *et al.*, in press**).

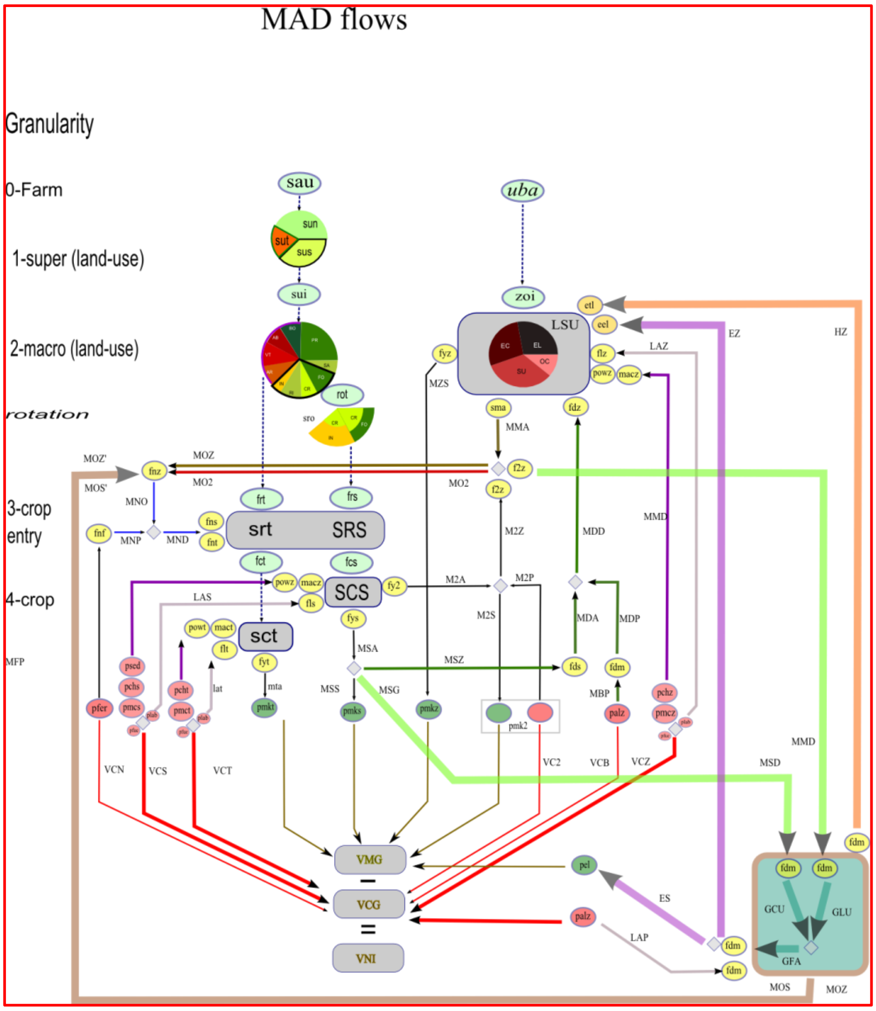

Fig. 3:1 MAD flow-chart (as *cited in* **Vitali *et al.*, in press**)

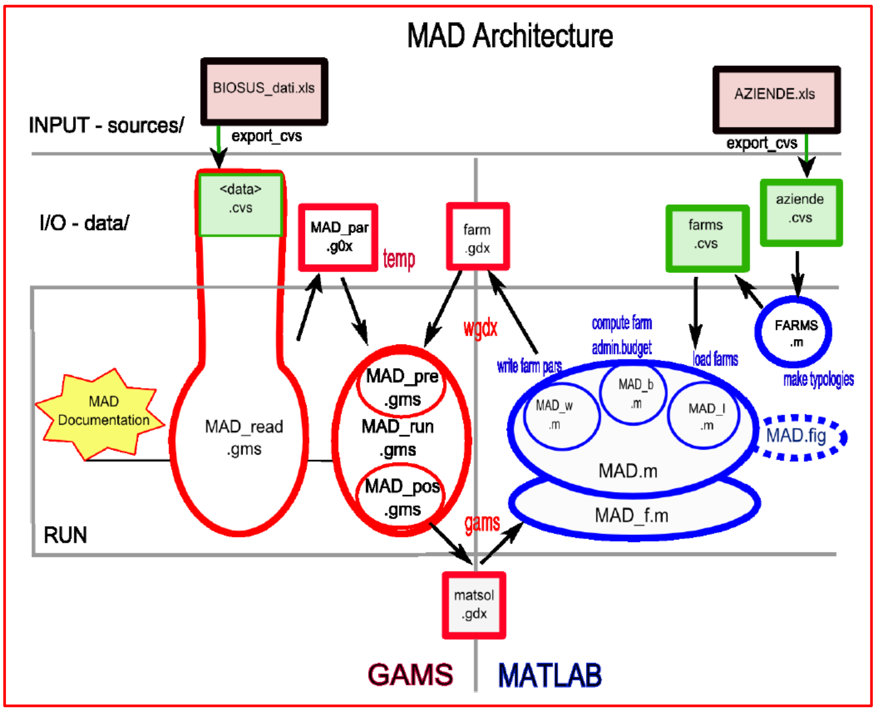

Fig. 3:2 MAD architecture (as *cited in* **Vitali *et al.*, in press**)

3.2.2.1. MAD activities

MAD considers four different levels of details (**Vitali *et al.*, in press**):

Level 1: Super activity

- LSU - livestock units, has been described by the animal breeding method;
- NAT - natural surfaces (woods, meadows), has been described from main natural species presents in such environment;
- ARB - tree crops, has been described from planted species and irrigation systems;
- SEM - arable crops and open field horticulture, has been described in terms of rotation schemes.

Level 2: Macro activity

This set of activities (Tables 3.1 & 3.2) gives details of super activities and macro activities with similar agro-technical activities (land use and livestock) (**Vitali *et al.*, in press**).

Table 3.1: List of macro-activities used by model related to land use

Super	**Macro**	**Land use**
NAT	BO	Wood
NAT	PR	Meadow
SEM	SA	Naturalized (set-aside)
SEM	FO	Forage
SEM	CR	Cereals
SEM	RI	Rice
SEM	IN	Intensive crop
IMP	AR	Fruit tree plant
IMP	VT	Grapevine
IMP	AB	Low input tree plant

Table 3.2: List of livestock related to macro activities

Super	**Macro**	**Livestock type**
ZOO	EL	Dairy cattle
ZOO	EC	Meat cattle
ZOO	OC	Sheeps and goats
ZOO	SU	Swines

Level 3: RICA-entry (rubrica)

Such a level corresponds to crop and activity families used by RICA-database (it: rubriche). Such families however are not homogeneous: some entries correspond to a very specific crop (*e.g.* durum wheat) while others collect several crops very different from market viewpoint (*e.g.* apple, cherry and peach are all together in a unique activity called 'temperate fruit') (**Vitali *et al.*, in press**).

Level 4: Crop production

When specified at the above levels, technical parameters cannot include productions, yields and related market prices. To solve this problem each activity has been linked to one specific crop depending on region, which also reflects main Italian DOPs[9] (typical of a territory). It means that for one region, there will be just one crop product (**Vitali *et al.*, in press**).

3.2.2.2. Farm parameterization

MAD has been developed to evaluate the optimal farm structure for whole period which is considered by analysis (10 years).

In MAD a farm is described by regional administrative (NUT2[10]) and environmental collocation (climate and slope).

Farm production is oriented to conventional or organic.

Farm eco-economic regime described by subsidy policy into three possible values:

- No subsidies;
- Actual subsidies (included for conventional and organic);
- PAC14[11] (included for greening conventional and organic).

[9] Denominazione di origine protetta
[10] Nomenclature of territorial units for statistics of EUROSTAT
[11] Politica agricola comunitaria

3.2.2.3. Farm activity partitioning

- Preliminary (pre-optimization) initial condition (parameters of super-activity);
- Tree crops intermediate granularity;
- Total Arable area;
- Livestock intermediate granularity.

3.2.2.4. Farm main products

In this section the yearly yield of farm commercial products of crops (tons) and livestock (kg) are calculated (**Vitali *et al.*, in press**):

- Tree crops yield;
- Field crops yield;
- Livestock products (meat and milk).

3.2.2.5. Farm secondary products

- Straw production;
- Fresh residues of tree crops;
- Manure production.

3.2.2.6. Livestock feeding

Diet requirements for livestock includes forage units (fu) requirements for energetic balance, ruminant functionality (for herbivorous), and protein requirements (pr) more relevant for granivorous (swines). Both parameters are calculated through two separate constraints, one to avoid minimum level of nutrition, the second to avoid any excess. Moreover diet nutrition requirements for livestock comes from on-farm production of forage crops and / or purchased from market (**Vitali *et al.*, in press**).

3.2.2.7. Fertility balance (N[12])

On-farm N requirements for trees and field crops, comes from on-farm manure production and / or N purchased from market. Add quantities of N fertilizers are calculated through two

[12] Nitrogen

separate constraints, one to avoid minimum level of N fertilizers (required for trees and field crops), the second to avoid any excess defined by Legal N load.

3.2.2.8. Labor requirements

On-farm Labor requirements contains: labor requirements for trees crops, field crops, and livestock breeding (h / ha and h / lsu).

3.2.2.9. Farm account balance

According to **Vitali *et al.* (in press**) farm net-income comes from subtract of the total costs (contains fixed and variable costs) from total gross margin (contains income of farm production and subsidies). Fixed costs come from RICA database and variable costs contain:

- Costs of seeds;
- Costs of fertilizers;
- Costs of pesticide and chemicals;
- Costs of machinery;
- Costs of fuel;
- Costs labor;
- Costs of feedstocks for animal diet nutrition.

Gross margin contain:

- Gross margin of trees crops (for main production only);
- Gross margin of field crops (for main and secondary production);
- Gross margin of livestock production (for main production only);
- Subsidies.

Prices change over time, so they are updated by means of a tax rate applied from an initial price and referring to an initial year which can be different for each resource.

3.2.2.10. Pre- and Post-processing

- Pre-computed parameters
    - Administrative budget (fixed costs come from RICA database);
    - Business-as-usual budget (subsides);

- Organic certification budget (related to variable costs of farm structure);
- CAP14 budget (subsides);

- Derived Indexes (post-optimization)

3.2.2.11. Environmental model

In MAD the environmental component has not an active role, as it is used to calculate environmental parameters and related indicators. Different orientations (conventional, organic) should result in different optimal farm structures with different income and possibly different level of carbon storage / emission. This approach can so be used to verify the existence of a correlation between orientation and GHG[13] emission reduction of net income.

The environmental model in MAD is computed in post-optimization. The variable described hereafter describe C[14] fluxes on an annual basis, which are related to transformation processes in vegetal and animal farm compartment, both under natural regime and management, all being related to GHG emissions (**Vitali *et al.*, in press**).

- C assimilated in natural surfaces;
- C assimilated in trees crops;
- C assimilated in field crops;
- C accumulated in woody tissue;
- C in natural woody residuals;
- C in trees pruning;
- C in crop residuals;
- C in manure;
- C emissions by livestock breeding;
- C potential accumulation in humus;
- C maximum in humus;
- C emissions from farm management.

[13] Greenhouse gases
[14] Carbon

3.2.3. Description of RAF model

RAF is a bio-energetic descriptive model in terms of sets of equations (or inequalities) runs by using GAMS code and GUI (Graphical Use Interface) works under MATLAB environment for optimization the objective function (Z) (maximization the net income for whole period which is considered by analysis). Model equations are used as constraints in terms of energy via convert energy crops and animal manure to biogas (energy carrier) and digestate (bio-fertilizer) by using anaerobic digestion (AD) technologies, agricultural growing and animal breeding practices.

The different variables, parameters and indexes of RAF model could be distinguished in four sets as illustrated in Fig. (3.3):

- Variables and parameters in lowercase for non-optimization data (**pre-optimization input data**);
- Variables in uppercase for optimization (**output data of optimization**);
- Variables in lowercase for post-optimization (**calculating after optimization from optimum data**) uses as a key design elements of on-farm biogas system;
- Indexes in subscript (while in GAMS they become literal values).

RAF model (Fig. 3.4) consists of 6 modules as shown below:

1- On-farm agricultural production module (from MAD model) (eqs. from 3.1 to 3.3);
2- On-farm livestock nutrition requirements module (from MAD model) (eqs. from 3.4 to 3.8);
3- On-farm energy consumption module (eqs. from 3.9 to 3.14);
4- On-farm labor requirements module (eq. 3.15);
5- On-farm account balance module (eq. 3.16);
6- Design of on-farm biogas system module (eqs. from 3.17 to 3.54).

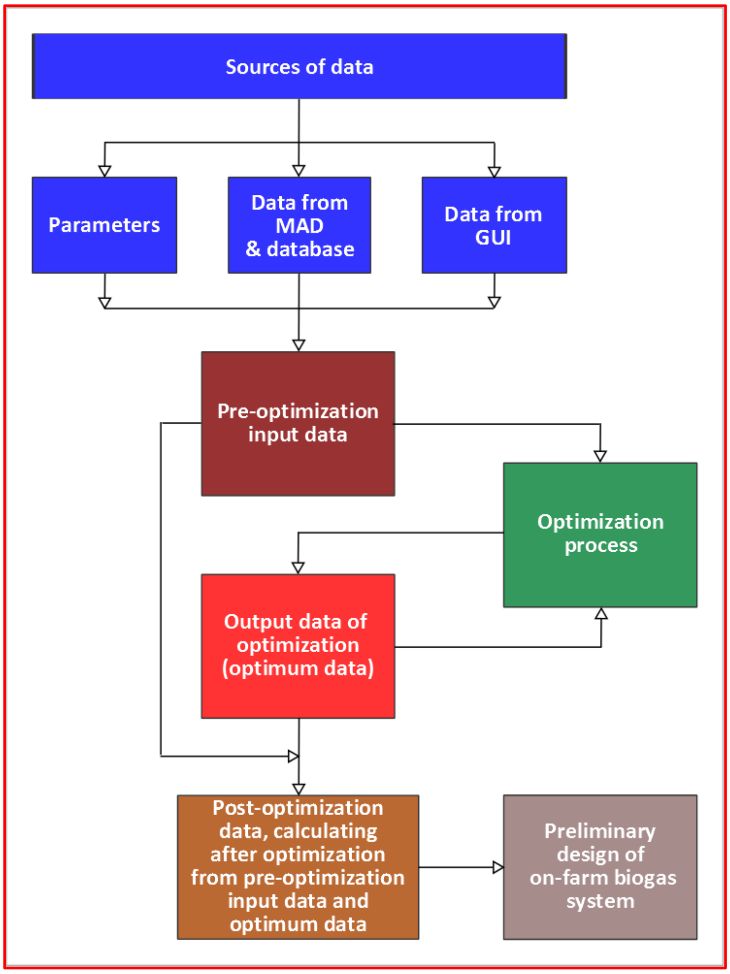

Fig. 3.3: Pathway of data processing in RAF model

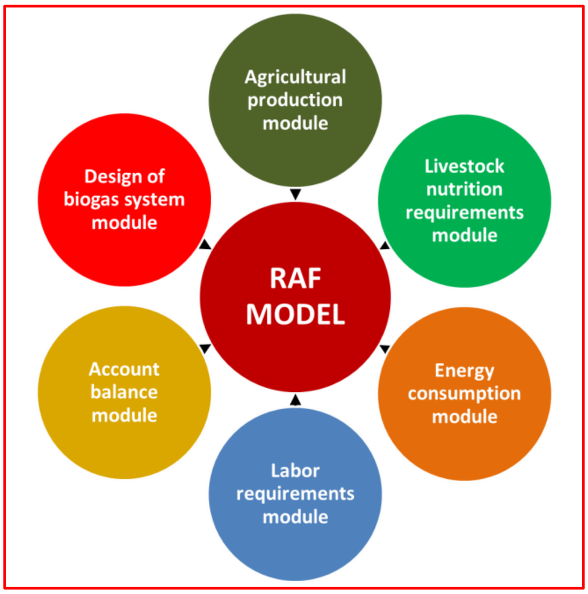

Fig. 3.4: RAF model architecture

3.2.3.1. Indexes list of RAF model

Indexes list of RAF model can be tabulated in Table (3.3):

Table 3.3: Indexes list of RAF model

Index	List of index
ca ⟶ tree crop index[15]	Cherries, poplar, grapevine, olive-tree and etc.
ce ⟶ energy crop index	Alfalfa, maize, sorghum and etc.
cg ⟶ greenhouses crop index	tomatoes, pepper, cucumber and etc.
cm ⟶ market diet index	alfalfa, maize, sorghum and etc.
cs ⟶ field crop index	Alfalfa, maize, sorghum, sunflower, wheat and etc.
cz ⟶ forage crop index	Alfalfa, maize, sorghum and etc.
di ⟶ diet nutrient index	forage unit and protein
sy ⟶ system index	psychrophilic, mesophilic and thermophilic
zo ⟶ zoo index	Dairy cattle, non-dairy cattle, buffalos, pigs and etc.

3.2.4. On-farm agricultural production module

This module discusses, calculates and optimizes the different on-farm areas allocated to cultivate different crops and trees (for different purpose), for realized the optimum total net income of on-farm agricultural productive activities.

3.2.4.1. Total surface area of farm

Constraint of the total surface area of farm (sau), consists of sum of allocated surface areas for agricultural production to cultivate different crops (for different purposes), allocated surface areas for different facilities to serve agricultural production, livestock production and energy (from biogas) production, surface area of set-aside and surface area of natural surface (**Vitali *et al.*, in press**), calculating according to the following equation:

$$sau = SAG + SLS + sgs + sun \qquad (3.1)$$

Where:

sau = Total surface area of farm (ha);
SAG = Allocated surface area for on-farm agricultural production (ha), SAG ≥ 0, see eq. (3.2);
SLS = Allocated surface area for on-farm livestock production (ha), SLS ≥ 0, see eq. (3.3);
sgs = Allocated surface area for on-farm biogas system (ha), see eq. (3.50);

[15] User should mention in how many years the trees go at regime, plant duration and planting costs

sun = Surface area of natural surface (ha).

3.2.4.2. Allocated surface area for on-farm agricultural production

Constraint of allocated surface area for on-farm agricultural production (SAG), consists of sum of different allocated surface areas to cultivate different crops (for different purposes, such as greenhouses, food, forage, energy and trees) (**Vitali *et al.*, in press**), calculating according to the following equation:

$$SAG = \sum_{cs} SCS_{cs} + \sum_{cg} SCS_{cg} + \sum_{ca} sut_{ca} \; ; \; SAG \leq saa \qquad (3.2)$$

Where:

SAG = Allocated surface area for on-farm agricultural production (ha), SAG ≥ 0;
SCS_{cs} = Allocated surface area for field crops cultivation (ha), $SCS_{cs} \geq 0$;
SCS_{cg} = Allocated surface area for greenhouses cultivation (ha), $SCS_{cg} \geq 0$;
sut_{ca} = Allocated surface area for trees (ha);
saa = On-farm available surface arable area (ha).

3.2.4.3. Allocated surface area for on-farm livestock production

Constraint of allocated surface area for on-farm livestock production (SLS), contains breeding corrals, milking chambers, young calves isolation corrals, pregnant animals isolation corrals and other facilities related to on-farm livestock production (**Wand and Doris, 2011 and Eurostat, 2012**), calculating according to the following equation:

$$SLS = \sum_{zo} (LSU_{zo} \; . \, alu_{zo}) \qquad (3.3)$$

Where:

SLS = Allocated surface area for on-farm livestock production (ha), SLS ≥ 0,
LSU_{zo} = Number of livestock units (lsu), $LSU_{zo} \geq 0$;
alu_{zo} = Surface area required per livestock unit for different on-farm breeding and production facilities (ha / lsu), see appendix Table (8.1).

3.2.5. On-farm livestock nutrition requirements module

Forage requirements for livestock includes forage units (fu) requirements for energetic balance, ruminant functionality (for herbivorous), and protein requirements (pr) more relevant for granivorous (swines). Both parameters are optimized through two separate constraints, one to avoid minimum level of nutrition, the second to avoid any excess.

3.2.5.1. Total nutrition required for livestock

Constraint array of total nutrition required (MDD_{di}) (from on-farm available production of forage and purchased from market) in terms of diet nutrients (fu and cp) for livestock feeding, based on dry matter content (**Harris, 1997; Jacobs, 2002; Moran, 2005; Department of Primary Industries, 2010; The Merck Veterinary Manual, 2010 and MLA, 2012**), calculating according to the following equation:

$$MDD_{di} = \sum_{zo} (LSU_{zo} \; . fdz_{zo,di}) \qquad (3.4)$$

Where:

MDD_{di} = Total nutrition required (from on-farm available production of forage and purchased from market) in terms of diet nutrients for livestock feeding, based on dry matter content (fu / year and cp / year), $MDD_{di} \geq 0$;

LSU_{zo} = Number of livestock units (lsu), $LSU_{zo} \geq 0$;

$Fdz_{zo,di}$ = Nutrition required for livestock unit in terms of diet nutrients, based on dry matter content (fu / lsu . year and cp / lsu . year), see appendix Table (8.2);

fu = Forage unit, is a forage value of 1 kg of barley (unit);

cp = Crude protein (kg).

3.2.5.2. Available nutrition for livestock from on-farm production of forage crops

Constraint array of available nutrition for livestock from on-farm production of forage crops in terms of diet nutrients, based on dry matter content (fu and cp) (MDA_{di}) (**Balliette, 1998; Strohbehn and Loy, 2007 and Hall *et al.,* 2009**), calculating according to the following equation:

$$MDA_{di} = \sum_{cz} (MSZ_{cz} \; . fds_{cz,di}) \qquad (3.5)$$

Where:

MDA_{di} = Available nutrition for livestock from on-farm production of forage crops in terms of diet nutrients, based on dry matter content (fu / year and cp / year), $MDA_{di} \geq 0$;

MSZ_{cz} = Mass of forage crops (silage), based on dry matter content (ton / year), $MSZ_{cz} \geq 0$, $MSZ_{cz} \in MSF_{cz}$;

$fds_{cz,di}$ = Nutrients content of forage crops available for livestock feeding in terms of diet nutrients, based on dry matter content (fu / ton and cp / ton), see appendix Table (8.3);

fu = Forage unit, is a forage value of 1 kg of barley (unit);

cp = Crude protein (kg).

3.2.5.3. Nutrition purchased for livestock from market

Constraint array of nutrition purchased from market for livestock feeding in terms of diet nutrients (fu and cp), based on dry matter content (MDP_{di}) (**Vitali *et al.*, in press**), calculating according to the following equation:

$$MDP_{di} = \sum_{cm}(MBP_{cm} \, . \, fdm_{cm,di}) \qquad (3.6)$$

Where:

MDP_{di} = Nutrition purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content (fu / year and cp / year), $MDP_{di} \geq 0$;

MBP_{cm} = Mass of diet feedstock purchased from market for livestock feeding, based on dry matter content (ton / year), $MBP_{cm} \geq 0$;

$fdm_{cm,di}$ = Nutrients content of diet feedstock purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content (fu / ton and cp / ton), see appendix Table (8.4).

fu = Forage unit, is a forage value of 1 kg of barley (unit);

cp = Crude protein (kg).

3.2.5.4. Minimum requirements of nutrition for livestock

Constraint array of guarantee the enough supply of nutrition for livestock, calculating according to the following equation:

$$MDA_{di} + MDP_{di} \geq MDD_{di} \qquad (3.7)$$

Where:

MDA_{di} = Available nutrition for livestock from on-farm production of forage crops in terms of diet nutrients, based on dry matter content (fu / year and cp / year), $MDA_{di} \geq 0$, see eq. (3.5);

MDP_{di} = Nutrition purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content (fu / year and cp / year), $MDP_{di} \geq 0$, see eq. (3.6);

MDD_{di} = Total nutrition required (from on-farm available production of forage and purchased from market) in terms of diet nutrients for livestock feeding, based on dry matter content (fu / year and cp / year), $MDD_{di} \geq 0$, see eq. (3.4);

fu = Forage unit, is a forage value of 1 kg of barley (unit);

cp = Crude protein (kg).

3.2.5.5. Maximum tolerance of nutrition for livestock

Constraint array of maximum tolerance of nutrition to avoid the surplus supply of nutrition, calculating according the following equation:

$$MDA_{di} + MDP_{di} \leq MDD_{di} \,.\, (1 + fdx) \qquad (3.8)$$

Where:

MDA_{di} = Available nutrition for livestock from on-farm production of forage crops in terms of diet nutrients, based on dry matter content (fu / year and cp / year), $MDA_{di} \geq 0$, see eq. (3.5);

MDP_{di} = Nutrition purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content (fu / year and cp / year), $MDP_{di} \geq 0$, see eq. (3.6);

fdx = Surplus tolerance factor of diet nutrients for livestock feeding = 5 % = 0.05;

MDD_{di} = Total nutrition required (from on-farm available production of forage and purchased from market) in terms of diet nutrients for livestock feeding, based on dry matter content (fu / year and cp / year), $MDD_{di} \geq 0$, see eq. (3.4);

fu = Forage unit, is a forage value of 1 kg of barley (unit);

cp = Crude protein (kg).

3.2.6. On-farm energy consumption module

Energy inputs can be characterized as direct or indirect (embedded) energy:

- Direct energy inputs are fuel and lubricants used in feed processing and for energizing of delivery machinery. The electrical energy is used for milking, milk cooling, water heating and pumping, lighting, ventilation, air heating, electrical fencing, manure handling, office and personnel working environment and etc. Conventional electricity consumption represents around 25 % of the fossil fuels consumed at the dairy farms and about 60 % of this energy comes from diesel fuel (**Bulletin of the International Dairy Federation, 2010**).

- Indirect energy is embedded in the products used on the farm. Indirect energy inputs are:

o Animal Feeding:

Depending on the livestock diet the impact of the feed production can vary due to the process to produce concentrates is more energy consuming than to produce fodder (**Barnett and Russell, 2010**). Pasture requires the lowest energy demand (0.84 MJ (0.23 kWh) / kg of dry matter (DM)) due to machines are used only for cultivation and fertilization operations.

o Energy of Building:

There are three ways to calculate the indirect energy input of buildings:

1- Estimation of indirect energy input by use of published calculation results of similar building types (e.g. on square meter and life-span basis). The advantage is easy and fast calculation, the disadvantage - possible lack of precision if no publications for adequate buildings are available and / or calculations do not discriminate between construction and operating energy input.

2- Calculation of the indirect energy input of a whole building based on construction elements ready-calculated on square meter or running meter basis. The advantage is that during the planning phase of a new building alternative construction solutions can be compared relatively fast. This approach is not very suitable for existing agricultural buildings, if the construction elements can only be identified by destructive investigations and / or if the building is too old to fit the construction elements and materials presently used. Due to there are many ways to assemble a construction parts from different materials a profound data base of construction elements is a precondition.

3- Calculation of a whole building based on construction materials and real input used. This can easily be done on buildings under construction following up the material or book-keeping data. This is nearly impossible when the book-keeping material of the erection phase is not available anymore or contains insufficient data. Average indirect energy input for farm buildings (80 years) by **Gaillard *et al.* (1997)** is 153 MJ / m^2 . year.

- Energy of machinery:
  Indirect energy input for machinery depends on the intensity of use, the date and location of manufacture and the span life of machinery. Machines are normally at the end of their life time recycled and only the manufacturing and maintenance energy is used for agricultural production.

3.2.6.1. On-farm thermal energy consumed for greenhouses warming

Constraint of on-farm thermal energy consumed for greenhouses warming (ETG), in Italy there are four main climate areas (south, middle, north and west coast) for greenhouses production (**Ross, 2001; NSW Government, 2010 and Campiotti *et al.,* 2011**), calculating according to the following equation:

$$ETG = \sum_{cg} SCS_{cg} \, . \, eth \, . \, 1.25 \qquad (3.9)$$

Where:

ETG = On-farm thermal energy consumed for greenhouses warming (kWh_{th} / year), ETG ≥ 0;

SCS_{cg} = Allocated surface area for greenhouses cultivation (ha), $SCS_{cg} \geq 0$;

eth = Thermal energy required for greenhouses warming (kWh_{th} / ha . year), see appendix Table (8.5);

1.25 = The heating efficiency is 80 % for biogas heating system (1.25 = 100 / 80).

3.2.6.2. On-farm thermal energy consumed for livestock production

Constraint of on-farm thermal energy consumed for livestock production (livestock corrals warming, hot water for washing milking equipment, sterilization and etc.) (ETD) (**Hyper Physics, 2000; Hörndahl, 2008 and The Engineering Tool Box, 2010**), calculating according to the following equation:

$$ETD = \sum_{zo}(LSU_{zo} \, . \, etl_{zo}) \, . \, 1.25 \qquad (3.10)$$

Where:

ETD = On-farm thermal energy consumed for livestock production (kWh_{th} / year), ETD ≥ 0;
LSU_{zo} = Number of livestock units (lsu), $LSU_{zo} \geq 0$;
etl_{zo} = Thermal energy required for livestock unit (kWh_{th} / lsu . year), see appendix Table (8.6);
1.25 = The heating efficiency is 80 % for biogas heating system (1.25 = 100 / 80).

3.2.6.3. Total on-farm thermal energy consumed

Constraint of total on-farm thermal energy consumed (ETC), refers to total thermal energy consumption for different on-farm facilities (greenhouses warming, livestock corrals warming, hot water for washing milking equipment, sterilization and etc.), calculating according to the following equation:

$$ETC = ETG + ETD \qquad (3.11)$$

Where:

ETC = Total on-farm thermal energy consumed (kWh_{th} / year), ETC ≥ 0;
ETG = On-farm thermal energy consumed for greenhouses warming (kWh_{th} / year), ETG ≥ 0, see eq. (3.9);
ETD = On-farm thermal energy consumed for livestock production (kWh_{th} / year), ETD ≥ 0, see eq. (3.10).

3.2.6.4. On-farm electrical energy consumed for greenhouses

Constraint of on-farm electrical energy consumed for greenhouses (EEG), refers to electrical energy consumption for different greenhouses equipment (lighting, heating, cooling, motors, pumps, fans for ventilation and etc.), in Italy there are four main climate areas (south, middle, north and west coast) for greenhouses production (**EC&M, 2002; für Mikrofonaufnahmetechnik und Tonstudiotechnik, 2002; Worldwide Power Products, 2008; Campiotti *et al.,* 2011; All About Circuits, 2012 and Campiotti *et al.,* 2012**), calculating according to the following equation:

$$EEG = \sum_{cg} SCS_{cg} \; . eeh \qquad (3.12)$$

Where:

EEG = On-farm electrical energy consumed for greenhouses (kWh_{el} / year), EEG ≥ 0;
SCS_{cg} = Allocated surface area for greenhouses cultivation (ha), $SCS_{cg} \geq 0$;
eeh **=** Electrical energy required for greenhouses (kWh_{el} / ha . year), see appendix Table (8.7).

3.2.6.5. On-farm electrical energy consumed for livestock production

Constraint of on-farm electrical energy consumed for livestock production (EED), refers to electrical energy consumption for different livestock production equipment (lighting, heating, cooling, milking equipment, motors, pumps, fans for ventilation and etc.) (**EC&M, 2002; für Mikrofonaufnahmetechnik und Tonstudiotechnik, 2002; Commercial Energy Advisor, 2008; Worldwide Power Products, 2008 and All About Circuits, 2012**), calculating according to the following equation:

$$EED = \sum_{zo} (LSU_{zo} \; . eel_{zo}) \qquad (3.13)$$

Where:

EED = On-farm electrical energy consumed for livestock production (kWh_{el} / year), EED ≥ 0;
LSU_{zo} = Number of livestock units (lsu), $LSU_{zo} \geq 0$;
eel_{zo} **=** Electrical energy required for livestock unit (kWh_{el} / lsu . year), see appendix Table (8.8).

3.2.6.6. Total on-farm electrical energy consumed

Constraint of total on-farm electrical energy consumed (EEC), refers to total electrical energy consumption for different on-farm equipment (lighting, heating, cooling, milking equipment, motors, pumps, fans for ventilation and etc.), calculating according to the following equation:

$$EEC = EEG + EED \tag{3.14}$$

Where:

EEC = Total on-farm electrical energy consumed (kWh_{el} / year), EEC ≥ 0;

EEG = On-farm electrical energy consumed for greenhouses (kWh_{el} / year), EEG ≥ 0, see eq. (3.12);

EED = On-farm electrical energy consumed for livestock production (kWh_{el} / year), EED ≥ 0, see eq. (3.13).

3.2.7. On-farm labor requirements module

3.2.7.1. Total number of labor required for operate on-farm biogas system

Constraint of total number of workers required for operating and maintenance of on-farm biogas system (LGS) (**Lovrenčec, 2010**), calculating according to the following equation:

$$LGS = EEA \, . \, lre \tag{3.15}$$

Where:

LGS = Total number of workers required for operating and maintenance of on-farm biogas system (worker / year), LGS ≥ 0;

EEA = Total net productive capacity of electrical energy from on-farm CHP unit of biogas (kWh_{el} / year), EEA ≥ 0, see eq. (3.53);

lre = Number of workers required for operating and maintenance of biogas system in terms of workers required for produced electrical energy unit (5^{-7} worker / kWh_{el} = 1 worker / 2 GWh_{el}), see appendix Table (8.9).

3.2.8. On-farm account balance module

3.2.8.1. Total net income of on-farm biogas system in year t

Constraint of total net income of on-farm biogas production in year t, based on electrical energy production from on-farm CHP unit (VGC), (**Karellas *et al.*, 2010; Ragazzoni, 2011 and Vitali *et al.*, in press**) calculating according to the following equation:

$$VGC = (EEA \,.\, (pem - vce)) - (fcg \,.\, ecp) \qquad (3.16)$$

Where:

VGC = Total net income of on-farm biogas production in year t, based on electrical energy production from on-farm CHP unit (euro / year), VGC ≥ 0;

EEA = Total net productive capacity of electrical energy from on-farm CHP unit of biogas (kWh_{el} / year), EEA ≥ 0, see eq. (3.53);

pem = Market price of electrical energy in year t (0.25 euro / kWh_{el} generated from CHP unit);

vce = Variable costs of biogas system in year t, based on electrical energy generated from on-farm CHP unit (0.04 euro / kWh_{el} generated from CHP unit);

fcg = Fixed costs of biogas system in year t, based on electrical capacity of on-farm CHP unit (500 euro / kWh_{el} . year of electrical CHP unit capacity);

ecp = Electrical capacity of on-farm CHP unit of biogas (kWh_{el}).

3.2.9. Design of on-farm biogas system module

This module (Fig. 3.5) discusses, calculates and optimize the different design criteria (variables) of on-farm biogas system uses biomass (co-digestion feedstock) in terms of quantities of energy crops and animal manure slurry available for biogas production by biochemical conversion technologies and use the produced biogas as source of energy (thermal and electrical) for meets the different on-farm energy requirements, in order to achieve on-farm self-sufficiency of energy, as a step to achieving the integrated agricultural sustainability.

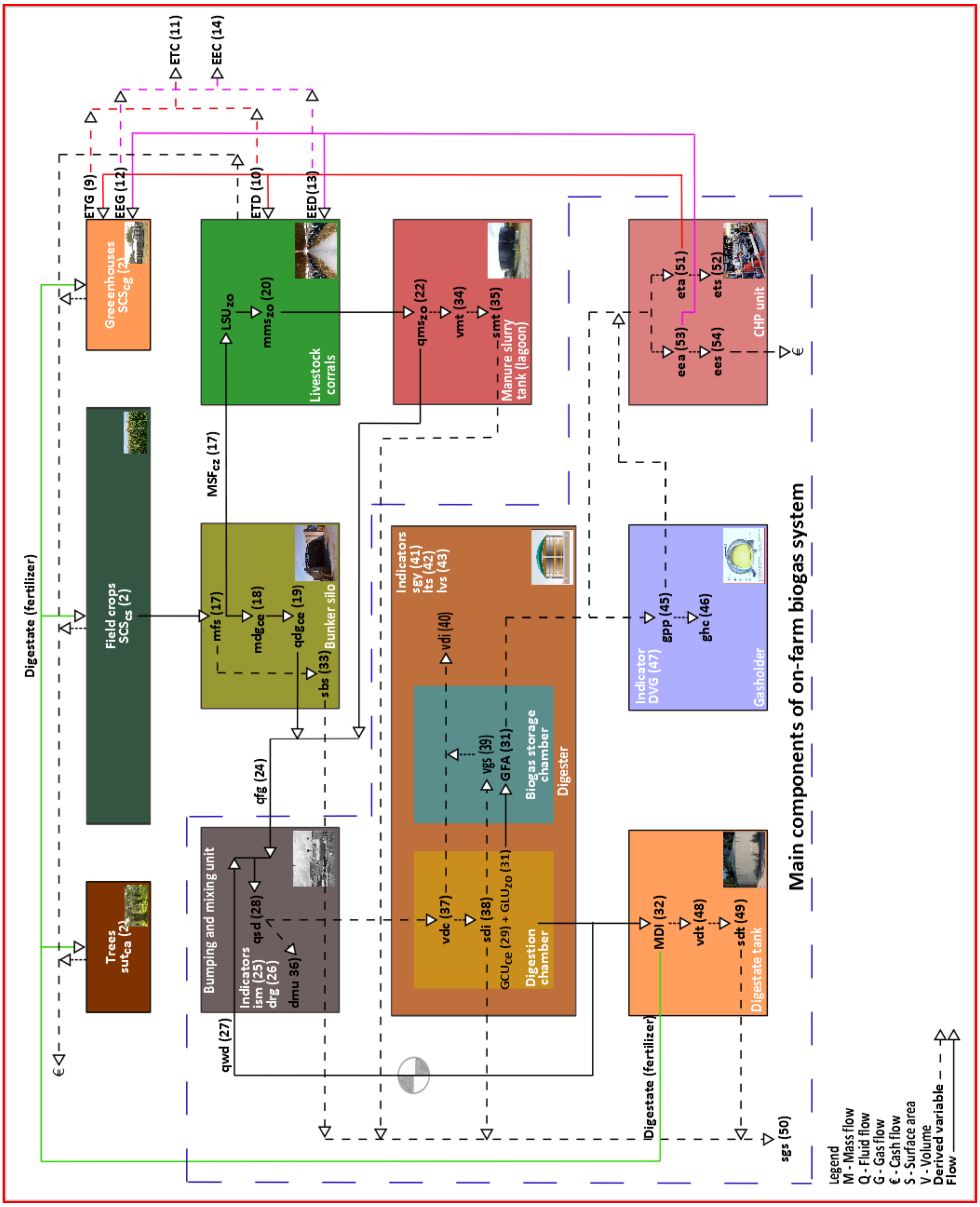

Fig. 3.5: Main components of on-farm biogas system, using silage and manure feedstock

Section I: Calculating constraints and dimensioning variables for on-farm biogas system design

3.2.9.1. Total mass of on-farm fresh silage available for livestock feeding and biogas production

Dimensioning variable of total mass of on-farm fresh silage available for livestock feeding and biogas production, produced from different on-farm crops (mfs), due to the seasonal production of fresh silage, it needs to storage in bunker silo to ensure continuous supply of silage for livestock feeding and biogas production throughout the year (default storage period for silage is 6 months or defined by user) (**Kaiser *et al.*, 2004 and Mickan, 2006**), calculating according to the following equation:

$$mfs = \left(\sum_{cz} MSF_{cz} + \sum_{ce} MSG_{ce}\right) . \; sps \qquad (3.17)$$

Where:

mfs = Total mass of on-farm fresh silage (refers to storage capacity of bunker silo for 6 months as default storage period) available for livestock feeding and biogas production (ton);

MSF_{cz} = Mass of fresh silage from different on-farm crops available for livestock feeding (contains TS from 30 to 40 % and MC from 60 to 70 %) (ton / year), $MSF_{cz} \in$ mfs, see appendix Table (8.10);

MSG_{ce} = Mass of fresh silage from different on-farm crops available for biogas production (contains TS from 30 to 40 % and MC from 60 to 70 %) (ton / year), $MSG_{ce} \in$ mfs, see appendix Table (8.10);

sps = Default storage period of silage (0.5 year).

3.2.9.2. Mass of on-farm air-dried silage available for biogas production

Constraint array of mass of air-dried silage available for biogas production, produced from different on-farm energy crops (MDG_{ce}) (**Kaiser *et al.*, 2004 and Mickan, 2006**), calculating according to the following equation:

$$MDG_{ce} = \frac{MSG_{ce}\,.\,dds}{dfs} \tag{3.18}$$

Where:

MDG_{ce} = Mass of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (ton / year), $MDG_{ce} \geq 0$, $MDG_{ce} \in MSG_{ce}$;

MSG_{ce} = Mass of fresh silage from different on-farm crops available for biogas production (contains TS from 30 to 40 % and MC from 60 to 70 %) (ton / year), $MSG_{ce} \geq 0$, see eqs. (3.17);

dds = Density of air-dried silage (contains TS from 70 to 90 % and MC from 10 to 30 %) (0.26 ton / m^3) (1 ton of air-dried silage = 3.85 m^3, so 1 m^3 = 0.26 ton);

dfs = Density of fresh silage (contains TS from 30 to 45 % and MC from 55 to 70 %) (0.6 ton / m^3).

3.2.9.3. Quantity of on-farm air-dried silage available for biogas production

Dimensioning variables array of quantity of on-farm air-dried silage available for biogas production, produced from on-farm energy crops (qdg_{ce}) (**Kaiser *et al.*, 2004 and Mickan, 2006**), calculating according to the following equation:

$$qdg_{ce} = \frac{MDG_{ce}}{dds} \tag{3.19}$$

Where:

qdg_{ce} = Quantity of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (m^3 / year), $qdg_{ce} \in MSG_{ce}$, see eq. (3.17);

MDG_{ce} = Mass of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (ton / year), see eq. (3.18);

dds = Density of air-dried silage (contains TS from 70 to 90 % and MC from 10 to 30 %) (0.26 ton / m^3) (1 ton of air-dried silage = 3.85 m^3, so 1 m^3 = 0.26 ton).

3.2.9.4. Mass of on-farm manure slurry available for biogas production

Constraint array of mass of on-farm manure slurry produced from livestock and available for biogas production (MMS_{zo}), refers to the mass of livestock excrements in terms of manure slurry (contains TS from 8 to 12 % and MC from 88 to 92 %) (**Landry *et al.*, 2002; Arora and**

Licht, 2004; Miner *et al.,* 2005; Ohio State University Extension, 2006 and Biogas Training Center, 2011), calculating according to the following equation:

$$MMS_{zo} = \frac{LSU_{zo} \; . \; alm_{zo} \; . \; sme_{zo} \; . \; 365}{1000} \qquad (3.20)$$

Where:

MMS_{zo} = Mass of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (ton / year), $MMS_{zo} \geq 0$;

LSU_{zo} = Number of livestock units (lsu), $LSU_{zo} \geq 0$;

alm_{zo} = Average live mass of livestock unit (kg of lsu mass / lsu), see appendix Table (8.11);

sme_{zo} = Average specific mass of excrements (kg of manure slurry / kg of lsu mass . day), see appendix Table (8.11);

365 = Number of days per year (day / year);

1000 = Conversion factor from kg to ton (kg / ton).

Observation:

On-farm biogas production system needs to integrate with manure slurry collection system in livestock corrals (such as flushed or scraped free-stall barns and dry-lots) and store the collected manure slurry in tank or lagoon. On the other hand use the straw as a manure bed (for absorption the animal urine) in livestock corrals is not allowed in case of applying on-farm biogas production and manure slurry collection systems (due to the high C / N ratio of straw it is not suitable for anaerobic digestion) and instead of use the manure bed as on-farm organic fertilizer for soil could be use the digestate produced from anaerobic digestion of silage and manure slurry as on-farm bio-fertilizer rich with soil nutrients.

3.2.9.5. Mass of on-farm air-dried manure available for biogas production

Constraint array of mass of on-farm air-dried manure available for biogas production (MDM_{zo}) (**Landry *et al.*, 2002; Arora and Licht, 2004; Miner *et al.,* 2005 and Ecochem, 2011**), calculating according to the following equation:

$$MDM_{zo} = MMS_{zo} \cdot cfm \tag{3.21}$$

Where:

MDM_{zo} = Mass of on-farm air-dried manure available for biogas production (ton / year), $MDM_{zo} \geq 0$, $MDM_{zo} \in MMS_{zo}$;

MMS_{zo} = Mass of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (ton / year), $MMS_{zo} \geq 0$, see eq. (3.20);

cfm = The conversion factor (in terms of mass) from manure slurry to air-dried manure **(**contains 85 % of TS content and 15 % of MC) = 12 %.

3.2.9.6. Quantity of on-farm manure slurry available for biogas production

Dimensioning variables array of quantity of on-farm manure slurry available for biogas production (qms_{zo}) (**Landry *et al.*, 2002; Arora and Licht, 2004; Miner *et al.,* 2005; Ohio State University Extension, 2006 and Ecochem, 2011**), calculating according to the following equation:

$$qms_{zo} = \frac{MMS_{zo}}{dms} \tag{3.22}$$

Where:

qms_{zo} = Quantity of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (m^3 / year);

MMS_{zo} = Mass of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (ton / year), see eq. (3.20);

dms = Density of manure slurry (contains TS from 8 to 12 % and MC from 88 to 92 %) (1 ton / m^3).

3.2.9.7. Total mass of on-farm feedstock available for biogas production

Dimensioning variable of total mass of on-farm feedstock available for biogas production (mfg), refers to the sum of mass of on-farm air-dried silage available for biogas production and mass of on-farm manure slurry available for biogas production, calculating according to the following equation:

$$mfg = \sum_{ce} MDG_{ce} + \sum_{zo} MMS_{zo} \quad (3.23)$$

Where:

mfg = Total mass of on-farm feedstock available for biogas production (ton / year);

MDG_{ce} = Mass of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (ton / year), see eq. (3.18);

MMS_{zo} = Mass of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (ton / year), see eq. (3.20).

3.2.9.8. Total quantity of on-farm feedstock available for biogas production

Dimensioning variable of total quantity of on-farm feedstock available for biogas production (qfg), refers to the sum of quantity of on-farm air-dried silage available for biogas production and quantity of on-farm manure slurry available for biogas production, according to the following equation:

$$qfg = \sum_{ce} qdg_{ce} + \sum_{zo} qms_{zo} \quad (3.24)$$

Where:

qfg = Total quantity of on-farm feedstock available for biogas production (m^3 / year);

qdg_{ce} = Quantity of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (m^3 / year), see eq. (3.19);

qms_{zo} = Quantity of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (m^3 / year), see eq. (3.22);

The best volumetric mixture ratio of $\sum_{ce}qdg_{ce}$: $\sum_{zo}qms_{zo}$ is 3 m^3 : 1 m^3 respectively (0.78 ton of air-dried silage : 1 ton of manure slurry) for obtain the maximum biogas yield in co-digestion process (**Saev and Simeonov, 2009 and Xie, 2011**).

3.2.9.9. Concentration of total solids at the Inlet of mixing unit

Service variable of concentration of total solids at the Inlet of mixing unit (ism), in case of co-digestion (using mixed substrate consists of air-dried silage and manure slurry), there is a need to calculating the concentration of TS for mixed substrate at the Inlet of mixing unit (**Al Seadi, 2001; Amours and Savoie, 2005; Mickan, 2006; Al Seadi *et al.*, 2008; Gottstein, 2010; Biogas a Renewable Biofuel, 2011; Biomass Energy Center, 2011; Extension, 2011;**

Delaval Global, 2012; Hollis, 2012; KWS, 2012 and The Dow Chemical Company, 2012), according to the following equation:

$$ism = \frac{\sum_{ce}(qdg_{ce} \, . \, tss_{ce}) + \sum_{zo}(qms_{zo} \, . \, tsm_{zo})}{mfg} \, . \, 100 \qquad (3.25)$$

Where:

ism = Concentration of TS (dry matter content) at the Inlet of mixing unit before dilution with water for mixed substrate consists of air-dried silage and manure slurry on the basis of wet-mass (%);

qdg_{ce} = Quantity of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (m^3 / year), see eq. (3.19);

tss_{ce} = Mass of TS for air-dried silage (ton / m^3), see appendix Table (8.12);

qms_{zo} = Quantity of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (m^3 / year), see eq. (3.22);

tsm_{zo} = Mass of TS for manure slurry (ton / m^3), see appendix Table (8.12);

mfg = Total mass of on-farm feedstock available for biogas production (ton / year), see eq. (3.23).

3.2.9.10. Dilution ratio of substrate required for biogas production

Service variable of dilution ratio of substrate required for biogas production (drg), refers to the ratio of concentration of TS in diluted substrate at the outlet of mixing unit to concentration of TS in substrate before dilution at the Inlet of mixing unit (**What Size Digester Do I Need, 1996; An and Preston, 1999; Kossmann *et al.*, 1999; Ciborowski, 2001; Dennis and Burke, 2001; United States Department of Agriculture, 2007; Al Seadi *et al.*, 2008; Balasubramaniyam *et al.*, 2008; Westerma *et al.*, 2008; Gottstein, 2010; Babaee and Shayegan, 2011; Biogas a Renewable Biofuel, 2011; Biomass Energy Center, 2011; Extension, 2011; Delaval Global, 2012; Hollis, 2012; KWS, 2012 and The Dow Chemical Company, 2012**), calculating according to the following equation:

$$drg = \frac{ots}{ism} \cdot 100 \qquad (3.26)$$

Where:

drg = Dilution ratio of substrate required for biogas production (%);

ots = Concentration of TS (dry matter content) in diluted substrate at the outlet of mixing unit, on the basis of wet-mass (8 %);

ism = Concentration of TS (dry matter content) at the Inlet of mixing unit before dilution with water for mixed substrate consists of air-dried silage and manure slurry on the basis of wet-mass (%), see eq. (3.25);

Observation:

its = Concentration of TS (dry matter content) in unmixed substrate (air-dried silage or manure slurry only) before dilution at the **Inlet** of mixing unit, on the basis of wet-mass (%), see appendix Table (8.13);

In case of use one type of feedstock (use silage or manure slurry only) can use (its), but in case of co-digestion (use mixed substrate of silage and manure slurry) can use (ism) instead of (its), see eq. (3.25).

3.2.9.11. Total Quantity of water required for substrate dilution

Dimensioning variable of total quantity of water required for substrate dilution (qwd) (**Al Seadi *et al.*, 2008; Gottstein, 2010; Biogas a Renewable Biofuel, 2011; Biomass Energy Center, 2011; Extension, 2011; Delaval Global, 2012; Hollis, 2012; KWS, 2012 and The Dow Chemical Company, 2012**), calculating according to the following equation:

$$qwd = qfg\,(\frac{100}{drg} - 1) \qquad (3.27)$$

Where:

qwd = Total quantity of water required for substrate dilution (m^3 / year) = (ton / year);

qfg = Total quantity of on-farm feedstock available for biogas production (m^3 / year), see eq. (3.24);

drg = Dilution ratio of substrate required for biogas production (%), see eq. (3.26).

3.2.9.12. Total quantity of diluted substrate input to digester

Dimensioning variable of total quantity of diluted substrate input to digester (qsd), refers to the sum of substrates quantities (air-dried silage and manure slurry available for biogas production) and water quantities required for diluted this substrates (for realize the dilution ratio required for biogas production), calculating according to the following equation:

$$qsd = qfg + qwd \tag{3.28}$$

Where:

qsd = Total quantity of diluted substrate input to digester (m^3 / year);

qfg = Total quantity of on-farm feedstock available for biogas production (m^3 / year), see eq. (3.24);

qwd = Total quantity of water required for substrate dilution (m^3 / year) = (ton / year), see eq. (3.27).

3.2.9.13. Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops

Constraint array of biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (GCU_{ce}) (**Banks, 2009; Centre and Redman, 2010; Knitter *et al.*, 2010; NNFCC, 2010; Dimpl and Blunck, 2011; Hopwood, 2011 and Shokri, 2011**), calculating according to the following equation:

$$GCU_{ce} = MSG_{ce} \, . \, gyc_{ce} \tag{3.29}$$

Where:

GCU_{ce} = Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (m^3 / year), $GCU_{ce} \geq 0$;

MSG_{ce} = Mass of fresh silage from different on-farm crops available for biogas production (contains TS from 30 to 40 % and MC from 60 to 70 %) (ton / year), $MSG_{ce} \geq 0$, $MSG_{ce} \in mfs$, see eq. (3.17);

gyc_{ce} = Biogas yield generated per mass unit of fresh silage from energy crops (m^3 / ton), see appendix Table (8.14).

3.2.9.14. Biogas yield generated, based on biogas yield per livestock unit

Constraint array of biogas yield generated, based on biogas yield per livestock unit (GLU_{zo}) (**British Biogen, 2000; Anaerobic Digestion, 2010; Knitter *et al.*, 2010; NNFCC, 2010; Timmerman and Rulkens, 2010; Irish Farmers Journal, 2011 and Biogas Technologies, 2012**), calculating according to the following equation:

$$GLU_{zo} = LSU_{zo} \,.\, gyl_{zo} \tag{3.30}$$

Where:

GLU_{zo} = Biogas yield generated, based on biogas yield per livestock unit (m^3 / year), $GLU_{zo} \geq 0$;

LSU_{zo} = Number of livestock units (lsu), $LSU_{zo} \geq 0$;

gyl_{zo} = Biogas yield generated from livestock unit (m^3/ lsu . year), see appendix Table (8.15).

3.2.9.15. Total on-farm biogas yield

Constraint of total on-farm biogas yield (GFA), refers to the sum of biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops and biogas yield generated, based on biogas yield per livestock unit, calculating according to the following equation:

$$GFA = \sum_{ce} GCU_{ce} + \sum_{zo} GLU_{zo} \tag{3.31}$$

Where:

GFA = Total on-farm biogas yield (m^3 / year), $GFA \geq 0$;

GCU_{ce} = Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (m^3 / year), $GCU_{ce} \geq 0$, see eq. (3.29);

GLU_{zo} = Biogas yield generated, based on biogas yield per livestock unit (m^3 / year), $GLU_{zo} \geq 0$, see eq. (3.30).

3.2.9.16. Total Mass of on-farm air-dried digestate after dewatering

Constraint of total mass of on-farm air-dried digestate after digestion process and dewatering (MDI) (**Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Lukehurst *et al.*, 2010 and Frandsen, 2011**), calculating by subtract the mass of biogas produced from the mass of air-dried feedstock (silage and manure) used for biogas production, according to the following equation:

$$MDI = \sum_{ce}(MDG_{ce} - (GCU_{ce} \, . \, dga)) + \sum_{zo}(MDM_{zo} - (GLU_{zo} \, . \, dga)) \qquad (3.32)$$

Where:

MDI = Total Mass of on-farm air-dried digestate after dewatering (ton / year), MDI ≥ 0;

MDG_{ce} = Mass of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (ton / year), MDG_{ce} ≥ 0, see eq. (3.18);

GCU_{ce} = Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (m^3 / year), GCU_{ce} ≥ 0, see eq. (3.29);

dga = Density of biogas (0.001265 ton /m^3);

MDM_{zo} = Mass of on-farm air-dried manure available for biogas production (ton / year), MDM_{zo} ≥ 0 see eq. (3.21);

GLU_{zo} = Biogas yield generated, based on biogas yield per livestock unit (m^3 / year), GLU_{zo} ≥ 0, see eq. (3.30);

Section II: Calculating of post-optimization values (key design elements[16] of on-farm biogas system)

3.2.9.17. Inner-surface area of bunker silo

Post-optimization calculating of inner-surface area of bunker silo (sbs), refers to the surface area required for storage on-farm production of fresh silage as a feedstock for livestock feeding and biogas production for specific storage period (default storage period for silage is 6 months or defined by user) (**Huhnke, 1990; Electrigaz Technologies Inc., 2007; Al Seadi *et al.*, 2008 and Kirchmeyr *et al.*, 2009**), calculating according to the following equation:

$$sbs = \frac{mfs}{dfs \, . \, hbs \, . \, 10000} \qquad (3.33)$$

Where:

sbs = Inner-surface area of bunker silo for storage fresh silage for livestock feeding and biogas production (ha);

[16] Some references refer to key design elements as "design criteria"

mfs = Total mass of on-farm fresh silage (refers to storage capacity of bunker silo for 6 months as default storage period) available for livestock feeding and biogas production (ton), see eq. (3.17);

dfs = Density of fresh silage stored in the bunker silo (contains TS from 30 to 40 % and MC from 60 to 70 %) (0.6 ton / m^3);

hbs = Default height of bunker silo (3 m);

10000 = Surface area of hectare (m^2 / ha).

3.2.9.18. Inner-volume of manure slurry tank or lagoon

Post-optimization calculating of inner-volume of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (vmt), refers to the capacity of manure slurry tank or lagoon required to storage the manure slurry from few days to few weeks for biogas production (**Landry *et al.*, 2002; Arora and Licht, 2004; Miner *et al.,* 2005; Ohio State University Extension, 2006 and Biogas Training Center, 2011**), calculating according to the following equation:

$$vmt = \frac{\sum_{zo} MMS_{zo} \cdot spm \cdot 1.15}{dms \cdot 365} \quad (3.34)$$

Where:

vmt = Inner-volume of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (m^3);

MMS_{zo} = Mass of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (ton / year), see eq. (3.20);

spm = Default storage period of manure slurry (40 days);

1.15 = Factor of operational inner-volume of manure slurry tank or lagoon (operational inner-volume should be more than 15 % of theoretical inner-volume);

dms = Density of manure slurry (contains TS from 8 to 12 % and MC from 88 to 92 %) (1 ton / m^3);

365 = Number of days per year (day / year).

3.2.9.19. Inner-surface area of manure slurry tank or lagoon

Post-optimization calculating of inner-surface area of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (smt) (**Landry *et al.*, 2002; Arora and Licht, 2004; Miner *et al.,* 2005; Ohio State University Extension, 2006 and Biogas Training Center, 2011**), calculating by dividing the inner-volume of manure slurry tank or lagoon, over the height of manure slurry tank or depth of lagoon, according to the following equation:

$$smt = \left(\frac{vmt}{hmt \, . \, 10000}\right) \qquad (3.35)$$

Where:

smt = Inner-surface area of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (ha);

vmt = Inner-volume of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (m^3), see eq. (3.34);

hmt = Default height of manure slurry tank or depth of lagoon (4 m);

10000 = Surface area of hectare (m^2 / ha).

3.2.9.20. Discharge of pumping and mixing unit

Post-optimization calculating of discharge of pumping and mixing unit (dmu), refers to the daily quantity of diluted substrate input to digester (**Institut für Energetik und Umwelt *et al.*, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007 and Al Seadi *et al.*, 2008**), calculating according to the following equation:

$$dmu = \frac{qsd \, . \, 1.15}{365} \qquad (3.36)$$

Where:

dmu = Discharge of pumping and mixing unit (m^3 / day);

qsd = Total quantity of diluted substrate input to digester (m^3 / year), see eq. (3.28);

1.15 = Factor of operational discharge of pumping and mixing unit (operational discharge should be more than 15 % of theoretical discharge);

365 = Number of days per year (day / year).

3.2.9.21. Inner-volume of digestion chamber

Post-optimization calculating of inner-volume of digestion chamber (with cylindrical shape) (vdc), refers to the capacity of digestion chamber (inside the digester) required to digest diluted substrate input to digester during the hydraulic retention time (hrt depending on temperature of digestion process) (**Sasse, 1988; Werner *et al.*, 1989; Biogas Process for Sustainable Development, 1992; Kossmann *et al.*, 1999; Wellinger, 1999; Dennis and Burke, 2001; Monnet, 2003; Al Seadi *et al.*, 2008; TATEDO, 2009 and Biogas Training Center, 2011**), calculating according to the following equation:

$$vdc = dmu \, . \, hrt_{sy} \tag{3.37}$$

Where:

vdc = Inner-volume of digestion chamber (with cylindrical shape) (m^3);
dmu = Discharge of pumping and mixing unit (m^3 / day), see eq. (3.36);
hrt_{sy} = Hydraulic retention time, retention time is defined by the user or use default (40 days for mesophilic system), see appendix Table (8.16).

3.2.9.22. Inner-surface area of digester

Post-optimization calculating of Inner-surface area of digester (with cylindrical shape) (sdi) (**Sasse, 1988; Werner *et al.*, 1989; Biogas Process for Sustainable Development, 1992; Kossmann *et al.*, 1999; Wellinger, 1999; Dennis and Burke, 2001; Monnet, 2003; Al Seadi *et al.*, 2008; TATEDO, 2009 and Biogas Training Center, 2011**), calculating by dividing the inner-volume of digestion chamber over the digestion chamber height, according to the following equation:

$$sdi = \frac{vdc}{hdc \, . \, 10000} \tag{3.38}$$

Where:

sdi = Inner-surface area of digester (with cylindrical shape) (ha);
vdc = Inner-volume of digestion chamber (with cylindrical shape) (m^3), see eq. (3.37);
hdc = Default height of digestion chamber (4 m);
10000 = Surface area of hectare (m^2 / ha).

3.2.9.23. Inner-volume of biogas storage chamber (biogas tight membranes)

Post-optimization calculating of inner-volume of biogas storage chamber (vgs), refers to the capacity of biogas storage chamber required to storage the produced biogas and established on the top of digestion chamber (low-pressure biogas tight membranes with dome shape). Usually, capacity from one to two days is recommended for use the biogas tight membranes (**Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; TATEDO, 2009; SATTLER AG & Ceno Membrane Technology GmbH, 2010 and ZORG, 2012**), calculating according to the following equation:

$$vgs = \frac{sdi\ .\ dst\ .\ 10000\ .\ 1.15}{3} \tag{3.39}$$

Where:

vgs = Inner-volume of biogas storage chamber (low-pressure biogas tight membranes with dome shape) (m^3);

sdi = Inner-surface area of digester (with cylindrical shape) (ha), see eq. (3.38);

dst = Distance between the static liquid surface in the digestion chamber and the top of biogas storage chamber (low-pressure biogas tight membranes with dome shape) (3 m).

10000 = Surface area of hectare (m^2 / ha);

1.15 = Factor of operational inner-volume of biogas chamber (operational inner-volume should be more than 15 % of theoretical inner-volume).

3.2.9.24. Total inner-volume of digester

Post-optimization calculating of total inner-volume of digester (vdi), refers to sum of the inner-volume of digestion chamber (with cylindrical shape) and inner-volume of biogas storage chamber (low-pressure biogas tight membranes with dome shape) (**Dennis and Burke, 2001; Monnet, 2003; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; TATEDO, 2009; SATTLER AG & Ceno Membrane Technology GmbH, 2010; Biogas Training Center, 2011 and ZORG, 2012**), calculating according to the following equation:

$$vdi = vdc + vgs \tag{3.40}$$

Where:

vdi = Total inner-volume of digester (m^3);

vdc = Inner-volume of digestion chamber (with cylindrical shape) (m^3), see eq. (3.37);

vgs = Inner-volume of biogas storage chamber (low-pressure biogas tight membranes with dome shape) (m^3), see eq. (3.39).

3.2.9.25. Specific gas yield

Post-optimization calculating of specific gas yield (sgy, service variable), refers to the daily volume of biogas produced from each cubic meter of total inner-volume of digester. sgy ranges from 0.2 under psychrophilic conditions to 0.6 under thermophilic conditions (**Werner *et al.,* 1989; Biogas Process for Sustainable Development, 1992; Rosillo-Calle *et al.*, 2007 and Nels, 2011**), calculating according to the following equation:

$$sgy = \frac{GFA}{vdi\ .\ 365} \tag{3.41}$$

Where:

sgy = Specific gas yield (m^3 of biogas / m^3 of total inner-volume of digester. day), see appendix Table (8.17);

GFA = Total on-farm biogas yield (m^3 / year), see eq. (3.31);

vdi = Total inner-volume of digester (m^3), see eq. (3.40);

365 = Number of days per year (day / year).

3.2.9.26. Digestion chamber loading, based on the daily mass of total solids input to digestion chamber

Post-optimization calculating of digestion chamber loading, based on the daily mass of TS input to digestion chamber (lts, service variable), refers to the daily mass of TS per each cubic meter of inner-volume of digestion chamber (**What Size Digester Do I Need, 1996; An and Preston, 1999; Kossmann *et al.*, 1999; Ciborowski, 2001; Dennis and Burke, 2001; United States Department of Agriculture, 2007; Al Seadi *et al.*, 2008; Balasubramaniyam *et***

***al.*, 2008; Westerma *et al.*, 2008 and Babaee and Shayegan, 2011**), calculating according to the following equation:

$$lts = \frac{(mfg + qwd)\ .\ ots\ .\ 1000}{vdc\ .\ 365} \tag{3.42}$$

Where:

lts = Digestion chamber loading, based on the daily mass of TS input to digestion chamber (kg of TS / m^3 of inner-volume of digestion chamber . day);

mfg = Total mass of on-farm feedstock available for biogas production (ton / year), see eq. (3.23);

qwd = Total Quantity of water required for substrate dilution (m^3 / year) = (ton / year), see eq. (3.27);

ots = Concentration of TS (dry matter content) in diluted substrate at the outlet of mixing unit, on the basis of wet-mass (8 %);

vdc = Inner-volume of digestion chamber (with cylindrical shape) (m^3), see eq. (3.37);

1000 = Conversion factor from ton to kg (kg / ton);

365 = Number of days per year (day / year).

Observation:

In general better digestion can be achieved at lower loadings. Thermophilic reactors appear to achieve greater conversions at high loadings while mesophilic reactors appear to achieve greater conversions at lower loadings.

3.2.9.27. Digestion chamber loading, based on the daily mass of volatile solids input to digestion chamber

Post-optimization calculating of digestion chamber loading, based on the daily mass of VS input to digestion chamber (lvs, service variable), refers to the daily mass of VS per each cubic meter of inner-volume of digestion chamber (**Kossmann *et al.*, 1999; Bio Fuel Cells Concepts for Local Energy, 2000; Ciborowski, 2001; Dennis and Burke, 2001; Balasubramaniyam *et al.*, 2008; Massart *et al.*, 2008; Westerma *et al.*, 2008; Babaee and Shayegan, 2011**), calculating according to the following equation:

$$lvs = lts \cdot cvs \qquad (3.43)$$

Where:

lvs = Digestion chamber loading, based on the daily mass of VS input to digestion chamber (kg of VS / m^3 of inner-volume of digestion chamber . day);

lts = Digestion chamber loading, based on the daily mass of TS input to digestion chamber (kg of TS / m^3 of inner-volume of digestion chamber . day), see eq. (3.42);

cvs = Concentration of VS in TS content of substrate, on the basis of wet-mass (85 %).

Observation:

- Completely mixed mesophilic anaerobic digester at an organic loading rate of 1.0 kg / m^3 of inner-volume of digestion chamber . day, achieved a peak VS conversion to gas of 64 %;
- Operated completely mixed thermophilic digesters at loadings of 6.5 to 10.78 kg / m^3 of inner-volume of digestion chamber . day, achieved 50 % VS conversion to gas;
- In typical anaerobic digester the digestion chamber loading is between 1 to 5 kg / m^3 of inner-volume of digestion chamber . day.

3.2.9.28. Gasholder capacity

Post-optimization calculating of low-pressure gasholder capacity (ghc), depends on the relative rates of biogas generation and biogas consumption (**Sasse, 1988; Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; SATTLER AG & Ceno Membrane Technology GmbH, 2010 and ZORG, 2012**). The gasholder must be designed to:

- Cover the peak (maximum) consumption rate of biogas (gmc), ghc ≥ gmc;
- Holds the biogas produced during the longest zero-consumption period (gzc), ghc ≥ gzc.

$$gpc = gmc \, . \, tmc \tag{3.44}$$

$$gpp = \frac{GFA \, . \, gzc}{8760} \tag{3.45}$$

Where:

gpc = Biogas peak consumption (m^3);

gmc = Maximum hourly biogas consumption (m^3/ h);

tmc = Time of maximum consumption (h);

gpp = Biogas peak production (m^3);

GFA = Total on-farm biogas yield (m^3 / year), see eq. (3.31);

8760 = number of hours per year (h / year);

gzc = Maximum zero-consumption period of biogas (10 h).

The larger value of gpc or gpp determines the capacity of the gasholder. Moreover a safety margin of 10 – 20 % should be taken into consideration for calculating the gasholder capacity, according to the following equation:

$$ghc = max \; (gpc, gpp) \, . \, 1.15 \tag{3.46}$$

Where:

ghc = Gasholder capacity (m^3);

1.15 = Safety margin for gasholder capacity.

3.2.9.29. Ratio of the digester volume to gasholder capacity

Post-optimization calculating of the ratio of inner-volume of digester to gasholder capacity (dvg, service variable) is a major factor with regard to the basic design of the biogas plant. For a typical agricultural biogas plant, the dvg amounts to somewhere between 3:1 and 10:1, with 5:1 to 6:1 occurring most frequently (**Sasse, 1988; Kossmann *et al.*, 1999; Institut für Energetik und Umwelt *et al.*, 2006; Lfu, 2007; Al Seadi *et al.*, 2008; SATTLER AG & Ceno Membrane Technology GmbH, 2010 and ZORG, 2012**), calculating according to the following equation:

$$dvg = \frac{vdi}{ghc} \qquad (3.47)$$

Where:

dvg = Ratio of the digester volume to gasholder capacity;

vdi = Total inner-volume of digester (m^3), see eq. (3.40);

ghc = Gasholder capacity (m^3), see eq. (3.46).

3.2.9.30. Inner-volume of digestate tank

Post-optimization calculating of inner-volume of digestate tank (vdt), refers to the capacity of digestate tank required to storage the digestate after digestion and dewatering processes (**Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Lukehurst *et al.*, 2010 and Frandsen, 2011**), calculating according to the following equation:

$$vdt = \frac{MDI\ .\ spd\ .\ 1.15}{ddi} \qquad (3.48)$$

Where:

vdt = Inner-volume of digestate tank (m^3);

MDI = Total mass of on-farm air-dried digestate after dewatering (ton / year), see eq. (3.32);

spd = Default storage period of digestate is 3 months (0.25 year);

ddi = Density of digestate (contains TS 90 % and MC 10 %) (1.1 ton / m^3);

1.15 = Factor of operational inner-volume of digestate tank (operational inner-volume should be more than 15 % of theoretical inner-volume).

3.2.9.31. Inner-surface area of digestate tank

Post-optimization calculating of inner-surface area of digestate tank (sdt) (**Lehtomäki, 2006; Electrigaz Technologies Inc., 2007; Lfu, 2007; Al Seadi *et al.*, 2008; Kirchmeyr *et al.*, 2009; Lukehurst *et al.*, 2010 and Frandsen, 2011**), calculating according to the following equation:

$$sdt = \frac{vdt}{hdt\ .\ 10000} \qquad (3.49)$$

Where:

sdt = Inner-surface area of digestate tank (ha);

vdt = Inner-volume of digestate tank (m^3), see eq. (3.48);

hdt = Height of digestate tank (3 m);

10000 = Surface area of hectare (m^2 / ha).

3.2.9.32. Allocated surface area for on-farm biogas system

Post-optimization calculating of the allocated surface area for on-farm biogas system (sgs), consists of sum of allocated surface areas for different facilities to serve on-farm biogas and energy production (**Vitali *et al.*, in press**), calculating according to the following equation:

$$sgs = (sbs + smt + sdi + sdt)\ .\ 1.10 \qquad (3.50)$$

Where:

sgs = Allocated surface area for on-farm biogas system (ha);

sbs = Inner-surface area of bunker silo for storage fresh silage for livestock feeding and biogas production (ha), see eq. (3.33);

smt = Inner-surface area of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (ha), see eq. (3.35);

sdi = Inner-surface area of digester (with cylindrical shape) (ha), see eq. (3.38);

sdt = Inner-surface area of digestate tank (ha), see eq. (3.49);

1.10 = Factor of operational surface area of biogas system (operational surface area should be more than 10 % of theoretical surface area), including the inner-surface area of pumping and mixing unit, inner-surface area of on-farm CHP unit of biogas, inner-surface area of gasholder and the inner-surface area of other facilities related to biogas system.

3.2.9.33. Total net productive capacity of thermal energy from on-farm CHP unit of biogas

Constraint of total net productive capacity of thermal energy from on-farm CHP unit of biogas (ETA) (**Kaiser *et al.*, 2004; Mickan, 2006; Kirchmeyr *et al.*, 2009; Knitter *et al.*, 2010;**

NNFCC, 2010; Biomass Energy Center, 2011 and Hopwood, 2011), calculating by multiply total on-farm biogas yield to specific conversion factor of biogas to net thermal energy, according to the following equation:

$$ETA = GFA \,.\, cft \,.\, uft \qquad (3.51)$$

Where:

ETA = Total net productive capacity of thermal energy from on-farm CHP unit of biogas (kWh_{th} / year), ETA ≥ 0;

GFA = Total on-farm biogas yield (m^3 / year), GFA ≥ 0, see eq. (3.31);

cft = Conversion factor of biogas to thermal energy = 2 kWh_{th} / m^3;

uft = Factor of useful thermal energy available for on-farm different uses. Usually, 33 % of the thermal energy produced is used for heating substrate inside the mixing unit and the digester and 67 % of the thermal energy produced is available for on-farm different uses = 0.67.

3.2.9.34. Surplus thermal energy produced from on-farm CHP unit of biogas

Post-optimization calculating of surplus thermal energy produced from on-farm CHP unit of biogas (ets), by subtract total on-farm thermal energy requirements from total net productive capacity of thermal energy from on-farm CHP unit of biogas, calculating according to the following equation:

$$ets = ETA - ETC \,;\, ETA \geq ETC \qquad (3.52)$$

Where:

ets = Surplus thermal energy produced from on-farm CHP unit of biogas (kWh_{th} / year);

ETA = Total net productive capacity of thermal energy from on-farm CHP unit of biogas (kWh_{th} / year), see eq. (3.51);

ETC = Total on-farm thermal energy consumed (kWh_{th} / year), see eq. (3.11).

3.2.9.35. Total net productive capacity of electrical energy from on-farm CHP unit of biogas

Constraint of total net productive capacity of electrical energy from on-farm CHP unit of biogas (EEA) (**Kaiser *et al.*, 2004; Mickan, 2006; Kirchmeyr *et al.*, 2009; Knitter *et al.*, 2010; NNFCC, 2010; Biomass Energy Center, 2011 and Hopwood, 2011**), calculating by multiply total on-farm biogas yield to specific conversion factor of biogas to net electrical energy, according to the following equation:

$$EEA = GFA \, . \, cfe \, . \, ufe \qquad (3.53)$$

Where:

EEA = Total net productive capacity of electrical energy from on-farm CHP unit of biogas (kWh_{el} / year), EEA ≥ 0;

GFA = Total on-farm biogas yield (m^3 / year), GFA ≥ 0, see eq. (3.31);

cfe = Conversion factor of biogas to electrical energy = 1.7 kWh_{el} / m^3;

ufe = Factor of useful electrical energy available for on-farm different uses. Usually, 10 % of the electrical energy produced is used for operate the biogas system and 90 % of the electrical energy produced is available for on-farm different uses = 0.9.

3.2.9.36. Surplus electrical energy produced from on-farm CHP unit of biogas

Post-optimization calculating of surplus electrical energy produced from on-farm CHP unit of biogas, which available for sell to the national electrical network (ees), by subtract total on-farm electrical energy requirements from total net productive capacity of electrical energy from on-farm CHP unit of biogas, calculating according to the following equation:

$$ees = EEA - EEC \, ; \, EEA \geq EEC \qquad (3.54)$$

Where:

ees = Surplus electrical energy produced from on-farm CHP unit of biogas, which available for sell to the national electrical network (kWh_{el} / year);

EEA = Total net productive capacity of electrical energy from on-farm CHP unit of biogas (kWh_{el} / year), see eq. (3.53);

EEC = Total on-farm electrical energy consumed (kWh_{el} / year), see eq. (3.14).

3.2.10. The objective function

The optimization process aims to maximize (Z), which refers to the total net income of farm for whole time which is considered by analysis, according to the following equation:

$$Z = \sum_t VIN_t \,.\, (1 + trn)^t \tag{3.55}$$

Where:

Z = The objective function for optimization;

VIN = Total net income of farm in year t (euro);

trn = Interest rate at year t (3%);

t = Reference year of farm account.

3.2.11. GAMS solver

The suggested GAMS solver to the RAF model is BDMLP solver.

4

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1. Case studies

For apply the RAF model and extracting the results, 2 hypothetical case studies based on realistic values have been developed.

4.1.1. Case study (A)

4.1.1.1. Farm parameterization

The parameterizations of hypothetical case study (A) of farm are:

- Farm undergo to north Italy conditions (climate and slope);
- Farm oriented to conventional agriculture (non-organic) and livestock production (dairy cattle);
- Farm gets actual subsidies;
- The period considered by analysis is 10 years.

4.1.1.2. Main products of farm

- Field crops yield (food, feed and energy crops);
- Livestock products (main products: milk and meat, and by-product: manure).

4.1.1.3. Apply on-farm biogas technology

For realized the sustainable development at the field of on-farm energy required and reduce the costs of on-farm energy consumed, the farm planning to establish an on-farm biogas system depends on co-digestion of energy crops and animal manure slurry for meets on-farm requirements of energy, moreover produce digestate (bio-fertilizers) for meets the on-farm requirements of fertilizers.

4.1.1.4. Description of farm structure

Farm structure can be defined by the way farm and their resources are organized to produce farm products (crops and livestock products). Description of farm structure for the hypothetical case study (A) is tabulated in Table (4.1):

Table 4.1: Description of farm structure for the hypothetical case study (A) (pre-optimization input data from GUI[17])

Technical term	Description	Value and unit
sau	Total surface area of farm	50 ha
SCS_{cs}	Allocated surface area for field crops cultivation	35 ha
SCS_{cz}	Allocated surface area for forage crops (medica, frumento-duro & altre-foraggere), $SCS_{cz} \in SCS_{cs}$	20 ha
SCS_{ce}	Allocated surface area for energy crops (alfalfa, maize & sorghum), $SCS_{ce} \in SCS_{cs}$	15 ha
SCS_{cg}	Allocated surface area for greenhouses cultivation	0 ha
sun	Surface area of natural surface (meadow)	15 ha
LSU_{zo}	Number of livestock units	50 dairy cows
pem	Market price of electrical energy	0.25 euro / kWh_{el}

4.1.1.5. Results of optimization process

The main results of hypothetical case study (A) are tabulated in Table (4.2):

Table 4.2: Optimum output data of hypothetical case study (A)

Eq.[18]	Tech.[19]	Value	Description and unit
3.2	SCS_{cs}	13.82 22.07	Allocated surface area of maize cultivation for biogas production (ha) Allocated surface area of medica, frumento-duro and altre-foraggere cultivation for forage (ha)
3.3	LSU_{zo}	52.50	Number of livestock units (ldairy cows)
3.3	SLS	0.105	Allocated surface area for on-farm livestock production (ha)
3.4	MDD_{di}	10500 fu 21000 cp	Total nutrition required (from on-farm available production of forage and purchased from market) in terms of diet nutrients for livestock feeding, based on dry matter content (fu / year and cp / year)
3.5	MDA_{di}	10491.09 fu 1316.19 cp	Available nutrition for livestock from on-farm production of forage crops in terms of diet nutrients, based on dry matter content (fu / year and cp / year)
3.6	MDP_{di}	8.90 fu 19683.80 cp	Nutrition purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content (fu / year and cp / year)
3.9	ETG	0	On-farm thermal energy consumed for greenhouses warming (kWh_{th} / year)
3.10	ETD	49218.75	On-farm thermal energy consumed for livestock production (kWh_{th} / year)
3.11	ETC	49218.75	Total on-farm thermal energy consumed (kWh_{th} / year)
3.12	EEG	0	On-farm electrical energy consumed for greenhouses (kWh_{el} / year)
3.13	EED	52500	On-farm electrical energy consumed for livestock production (kWh_{el} / year)
3.14	EEC	52500	Total on-farm electrical energy consumed (kWh_{el} / year)
3.15	LGS	1	Total number of workers required for operating and maintenance of on-farm biogas system (worker / year)
3.16	VGC	20192.40	Total net income of on-farm biogas production in year t, based on electrical energy production from on-farm CHP unit (euro / year)
3.17	mfs	261.14	Total mass of on-farm fresh silage (refers to storage capacity of bunker silo for 6 months as default storage period) available for livestock feeding and biogas production (ton)
3.18	MDG_{ce}	217.07	Mass of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (ton / year)
3.19	qdg_{ce}	834.88	Quantity of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (m^3 / year)
3.20	MMS_{zo}	1218.73	Mass of on-farm manure slurry available for biogas production (contains TS from 8 to

[17] Graphical use interface
[18] Equation number
[19] Technical term

Eq.[18]	Tech.[19]	Value	Description and unit
			12 % and MC from 88 to 92 %) (ton / year)
3.21	MDM_{zo}	146.24	Mass of on-farm air-dried manure available for biogas production (ton / year)
3.22	qms_{zo}	1218.73	Quantity of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (m^3 / year)
3.23	mfg	1435.80	Total mass of on-farm feedstock available for biogas production (ton / year)
3.24	qfg	2053.62	Total quantity of on-farm feedstock available for biogas production (m^3 / year)
3.25	ism	19.65	Concentration of TS (dry matter content) at the Inlet of mixing unit before dilution with water for mixed substrate consists of air-dried silage and manure slurry on the basis of wet-mass (%)
3.26	drg	40.71	Dilution ratio of substrate required for biogas production (%)
3.27	qwd	2991.22	Total quantity of water required for substrate dilution (m^3 / year) = (ton / year)
3.28	qsd	5044.84	Total quantity of diluted substrate input to digester (m^3 / year)
3.29	GCU_{ce}	110204.93	Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (m^3 / year)
3.30	GLU_{zo}	30450	Biogas yield generated, based on biogas yield per livestock unit (m^3 / year)
3.31	GFA	140654.93	Total on-farm biogas yield (m^3 / year)
3.32	MDI	186.26	Total Mass of on-farm air-dried digestate after dewatering (ton / year)
3.33	sbs	0.01451	Inner-surface area of bunker silo for storage fresh silage for livestock feeding and biogas production (ha)
3.34	vmt	153.59	Inner-volume of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (m^3)
3.35	smt	0.0038	Inner-surface area of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (ha)
3.36	dmu	15.89	Discharge of pumping and mixing unit (m^3 / day)
3.37	vdc	635.78	Inner-volume of digestion chamber (with cylindrical shape) (m^3)
3.38	sdi	0.0159	Inner-surface area of digester (with cylindrical shape) (ha);
3.39	vgs	182.78	Inner-volume of biogas storage chamber (low-pressure biogas tight membranes with dome shape) (m^3)
3.40	vdi	818.57	Total inner-volume of digester (m^3)
3.41	sgy	0.4708	Specific gas yield (m^3 of biogas / m^3 of total inner-volume of digester. day)
3.42	lts	1.52	Digestion chamber loading, based on the daily mass of TS input to digestion chamber (kg of TS / m^3 of inner-volume of digestion chamber . day)
3.43	lvs	1.29	Digestion chamber loading, based on the daily mass of VS input to digestion chamber (kg of VS / m^3 of inner-volume of digestion chamber . day)
3.45	gpp	160.56	Biogas peak production (m^3)
3.46	ghc	184.64	Gasholder capacity (m^3)
3.47	dvg	4.43	Ratio of the digester volume to gasholder capacity
3.48	vdt	48.45	Inner-volume of digestate tank (m^3)
3.49	sdt	0.0016	Inner-surface area of digestate tank (ha)
3.50	sgs	0.0394	Allocated surface area for on-farm biogas system (ha)
3.51	ETA	188477.60	Total net productive capacity of thermal energy from on-farm CHP unit of biogas (kWh_{th} / year)
3.52	ets	139258.85	Surplus thermal energy produced from on-farm CHP unit of biogas (kWh_{th} / year)
3.53	EEA	215202.04	Total net productive capacity of electrical energy from on-farm CHP unit of biogas (kWh_{el} / year)
3.54	ees	162702.04	Surplus electrical energy produced from on-farm CHP unit of biogas, which available for sell to the national electrical network (kWh_{el} / year)

4.1.1.6. Recommendations of biogas technology apply for case study (A)

A- Anaerobic digester

According to the output data of optimization from RAF model for case study (A) could recommend use the **wet anaerobic digestion process with mesophilic continuous system equipped with completely stirred tank reactor (CSTR) integrates with pumping system equipped with positive displacement pumps (progressing cavity pumps), suitable for co-digestion process for feedstock contains high content of silage with animal manure slurry.**

CSTR usually vertical circular tanks with hard or flexible membrane cover that store biogas. Tanks can be designed in a vertical (top mounted mixer) or flat (side mixers) configuration. CSTR are always mechanically stirred. The fresh feedstock enters the tank and is immediately mixed with the existing, partially digested material. Biogas production proceeds without any interruption from the loading and unloading of the waste material. To optimize the digestion process of the anaerobic bacteria, the digester should be kept at a constant temperature. Typically, a portion of the biogas generated is used to heat the contents of the digester, or the coolant from a biogas-powered generator is returned to a heat exchanger inside the digester tank. The temperature of the substrate inside digester is around 36 °C and the residence time of substrate (HRT) is around 35 days under mesophilic system.

Main components of CSTR:

- Mixing tank;
- Digester equipped with mixing, heating and biogas recovery systems;
- Effluent storage system;
- Biogas utilization system.

Advantages of CSTR:

- Efficient;
- Can digest different feedstocks contains different levels of dry matter;
- Can digest energy crops and by-products with animal manure;
- Good mixing of feedstocks;

- Good solid degradation;
- Can be used with either flush or scrape systems;
- Works well with flush and scrape systems (systems of manure collection from Corrals);
- The manure tanks, which already exist in farms could be converted to biogas digesters by equip them with isolation, stirring and heating systems which leading to construct cheap digester of biogas.

Disadvantages of CSTR:

- Relatively expensive;
- No guarantee on how much time the material remains in the tank (HRT);
- Requires mechanical mixing system;
- Bacteria wash out.

B- Combined heat and power (CHP) unit

According to the output data of optimization from RAF model for case study (A) could recommend use on-farm CHP unit of biogas with electrical capacity (ecp) 50 kWh_{el}, see eq. (3.16).

C- Total costs and income of on-farm biogas system

In case of establish on-farm biogas system with the recommended (CSTR) digester type, the total fixed costs of establish the on-farm biogas system are 250000 Euro (25000 Euro / year), while the variable costs are 86081 Euro (8608.1 Euro / year) during the span life of on-farm biogas system (10 years). The total costs (fixed and variable) of on-farm biogas system are 336081 Euro (33608.1 Euro / year), see Tables (2.13 and 2.14) and eq. (3.16).

The total net income of on-farm biogas system is 201924.3 Euro (20192.4 Euro / year) during span life, presents 60 % of the total costs of on-farm biogas system.

4.1.2. Case study (B)

4.1.2.1. Farm parameterization

The parameterizations of hypothetical case study (B) of farm are:

- Farm undergo to north Italy conditions (climate and slope);
- Farm oriented to conventional agriculture (non-organic) and livestock co-breeding production (meat cattle and pigs);
- Farm gets actual subsidies;
- The period considered by analysis is 10 years.

4.1.2.2. Main products of farm

- Field crops yield (food, feed and energy crops);
- Tree crops yield (wood);
- Livestock products (main product: meat and by-product: manure).

4.1.2.3. Apply on-farm biogas technology

For realized the sustainable development at the field of on-farm energy required and reduce the costs of on-farm energy consumed, the farm planning to establish an on-farm biogas system depends on co-digestion of energy crops and animal manure slurry for meets on-farm requirements of energy, moreover produce digestate (bio-fertilizers) for meets the on-farm requirements of fertilizers.

4.1.2.4. Description of farm structure

Farm structure can be defined by the way farm and their resources are organized to produce farm products (crops and livestock products). Description of farm structure for the hypothetical case study (B) is tabulated in Table (4.3):

Table 4.3: Description of farm structure for the hypothetical case study (B) (pre-optimization input data from GUI)

Technical term	Description	Value and unit
sau	Total surface area of farm	50 ha
SCS_{cs}	Allocated surface area for field crops cultivation	45 ha
SCS_{cz}	Allocated surface area for forage crops (medica, altre-foragger & frumento-duro), $SCS_{cz} \in SCS_{cs}$	35 ha
SCS_{ce}	Allocated surface area for energy crops (alfalfa, maize & sorghum), $SCS_{ce} \in SCS_{cs}$	10 ha
SCS_{cg}	Allocated surface area for greenhouses cultivation	0 ha
sut_{ca}	Allocated surface area for trees (wood)	5 ha
LSU_{zo}	Number of livestock units	150 meat calf & 200 pig
pem	Market price of electrical energy	0.25 euro / kWh_{el}

4.1.2.5. Results of optimization process

The main results of hypothetical case study (B) are tabulated in Table (4.4):

Table 4.4: Optimum output data of hypothetical case study (B)

Eq.[20]	Tech.[21]	Value	Description and unit
3.2	SCS_{cs}	13.87 35.18	Allocated surface area of maize cultivation for biogas production (ha) Allocated surface area of medica, altre-foragger and frumento-duro cultivation for forage (ha)
3.3	LSU_{zo}	157.50	Number of livestock units (meat calf)
3.3	SLS	0.189	Allocated surface area for on-farm livestock production (ha)
3.4	MDD_{di}	47250 fu 110250 cp	Total nutrition required (from on-farm available production of forage and purchased from market) in terms of diet nutrients for livestock feeding, based on dry matter content (fu / year and cp / year)
3.5	MDA_{di}	47202.79 fu 5921.97 cp	Available nutrition for livestock from on-farm production of forage crops in terms of diet nutrients, based on dry matter content (fu / year and cp / year)
3.6	MDP_{di}	47.20 fu 104328.02 cp	Nutrition purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content (fu / year and cp / year)
3.9	ETG	0	On-farm thermal energy consumed for greenhouses warming (kWh_{th} / year)
3.10	ETD	98437.50	On-farm thermal energy consumed for livestock production (kWh_{th} / year)
3.11	ETC	98437.50	Total on-farm thermal energy consumed (kWh_{th} / year)
3.12	EEG	0	On-farm electrical energy consumed for greenhouses (kWh_{el} / year)
3.13	EED	78750	On-farm electrical energy consumed for livestock production (kWh_{el} / year)
3.14	EEC	78750	Total on-farm electrical energy consumed (kWh_{el} / year)
3.15	LGS	1	Total number of workers required for operating and maintenance of on-farm biogas system (worker / year)
3.16	VGC	22558.70	Total net income of on-farm biogas production in year t, based on electrical energy production from on-farm CHP unit (euro / year)
3.17	mfs	299.50	Total mass of on-farm fresh silage (refers to storage capacity of bunker silo for 6 months as default storage period) available for livestock feeding and biogas production (ton)
3.18	MDG_{ce}	217.90	Mass of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (ton / year)
3.19	qdg_{ce}	838.11	Quantity of on-farm air-dried silage available for biogas production (contains TS from 70 to 90 % and MC from 10 to 30 %) (m^3 / year)
3.20	MMS_{zo}	2742.15	Mass of on-farm manure slurry available for biogas production (contains TS from 8 to

[20] Equation number
[21] Technical term

Eq.[20]	Tech.[21]	Value	Description and unit
			12 % and MC from 88 to 92 %) (ton / year)
3.21	MDM_{zo}	329.05	Mass of on-farm air-dried manure available for biogas production (ton / year)
3.22	qms_{zo}	2742.15	Quantity of on-farm manure slurry available for biogas production (contains TS from 8 to 12 % and MC from 88 to 92 %) (m^3 / year)
3.23	mfg	2960.06	Total mass of on-farm feedstock available for biogas production (ton / year)
3.24	qfg	3580.26	Total quantity of on-farm feedstock available for biogas production (m^3 / year)
3.25	ism	14.70	Concentration of TS (dry matter content) at the Inlet of mixing unit before dilution with water for mixed substrate consists of air-dried silage and manure slurry on the basis of wet-mass (%)
3.26	drg	54.42	Dilution ratio of substrate required for biogas production (%)
3.27	qwd	2998.52	Total quantity of water required for substrate dilution (m^3 / year) = (ton / year)
3.28	qsd	6578.79	Total quantity of diluted substrate input to digester (m^3 / year)
3.29	GCU_{ce}	110630.76	Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (m^3 / year)
3.30	GLU_{zo}	68512.50	Biogas yield generated, based on biogas yield per livestock unit (m^3 / year)
3.31	GFA	179143.26	Total on-farm biogas yield (m^3 / year)
3.32	MDI	321.21	Total Mass of on-farm air-dried digestate after dewatering (ton / year)
3.33	sbs	0.01664	Inner-surface area of bunker silo for storage fresh silage for livestock feeding and biogas production (ha)
3.34	vmt	345.58	Inner-volume of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (m^3)
3.35	smt	0.0086	Inner-surface area of manure slurry tank or lagoon (with cylindrical, square or rectangular shape) (ha)
3.36	dmu	20.72	Discharge of pumping and mixing unit (m^3 / day)
37	vdc	829.10	Inner-volume of digestion chamber (with cylindrical shape) (m^3)
3.38	sdi	0.0207	Inner-surface area of digester (with cylindrical shape) (ha);
3.39	vgs	238.36	Inner-volume of biogas storage chamber (low-pressure biogas tight membranes with dome shape) (m^3)
3.40	vdi	1067.47	Total inner-volume of digester (m^3)
3.41	sgy	0.4598	Specific gas yield (m^3 of biogas / m^3 of total inner-volume of digester. day)
3.42	lts	1.57	Digestion chamber loading, based on the daily mass of TS input to digestion chamber (kg of TS / m^3 of inner-volume of digestion chamber . day)
3.43	lvs	1.33	Digestion chamber loading, based on the daily mass of VS input to digestion chamber (kg of VS / m^3 of inner-volume of digestion chamber . day)
3.45	gpp	204.50	Biogas peak production (m^3)
3.46	ghc	235.17	Gasholder capacity (m^3)
3.47	dvg	4.53	Ratio of the digester volume to gasholder capacity
3.48	vdt	83.72	Inner-volume of digestate tank (m^3)
3.49	sdt	0.0028	Inner-surface area of digestate tank (ha)
3.50	sgs	0.0537	Allocated surface area for on-farm biogas system (ha)
3.51	ETA	240051.97	Total net productive capacity of thermal energy from on-farm CHP unit of biogas (kWh_{th} / year)
3.52	ets	141614.47	Surplus thermal energy produced from on-farm CHP unit of biogas (kWh_{th} / year)
3.53	EEA	274089.20	Total net productive capacity of electrical energy from on-farm CHP unit of biogas (kWh_{el} / year)
3.54	ees	195339.20	Surplus electrical energy produced from on-farm CHP unit of biogas, which available for sell to the national electrical network (kWh_{el} / year)

4.1.2.6. Recommendations for case study (B)

A- Anaerobic digester

According to the output data of optimization from RAF model for case study (B) could recommend use the **wet anaerobic digestion process with continuous system equipped with plug flow digester integrates with pumping system equipped centrifugal (rotating) pumps, suitable for co-digestion process for feedstock contains relative low content of silage with animal manure slurry**.

The plug flow digester is usually horizontal digester consists of rectangular tank that are half buried with a hard or flexible membrane cover installed to collect the biogas produced. The feedstock needs to be relatively thick (contains 8 – 12 % of DM) to ensure that feedstock movement maintains the plug flow effect. These digesters are generally not mechanically mixed. Feedstock enters at one end, pushing older substrate forward until it exits. Some systems will re-circulate substrate from the end of tank to inoculate the new material entering and speed up the degradation process. The residence time of substrate (HRT) from 20 to 40 days.

Main components of plug flow digester:

- Mixing tank;
- Digester equipped with heat exchanger and biogas recovery system;
- Effluent storage structure;
- Biogas utilization system.

Advantages of plug flow digester:

- Relatively Inexpensive;
- Simple to install and operate;
- Fit for livestock manure digestion;
- Works well with scrape systems (systems of manure collection from Corrals);
- Produces high quality fertilizers.

Disadvantages:

- Feedstock must contains more than 8 % of DM;
- Susceptible to contaminants (can’t be used with sand bedding);

- Poor mixing of feedstock;
- Poor yield of biogas;
- Nutrients and solids accumulate in bottom of digester, which lead to reducing useable volume of digester;
- Poor solids degradation;
- Membrane-top subject to weather (wind and snow);
- Bacteria wash out.

B- Combined heat and power (CHP) unit

According to the output data of optimization from RAF model for case study (B) could recommend use on-farm CHP unit of biogas with electrical capacity (ecp) 50 kWh_{el}, see eq. (3.16).

C- Total costs and income of on-farm biogas system

In case of establish on-farm biogas system with the recommended (CSTR) digester type, the total fixed costs of establish the on-farm biogas system are 250000 Euro (25000 Euro / year), while the variable costs are 109635.7 Euro (10963.6 Euro / year) during the span life of on-farm biogas system (10 years). The total costs (fixed and variable) of on-farm biogas system are 359635.7 Euro (45963.6 Euro / year), see Tables (2.13 and 2.14) and eq. (3.16).

The total net income of on-farm biogas system is 325587.3 Euro (32558.7 Euro / year) during span life, presents 90 % of the total costs of on-farm biogas system.

5

SUMMARY AND CONCLUSION

5. SUMMARY AND CONCLUSION

5.1. Introduction

Biogas is a non-conventional, promising renewable energy carrier, which combines the disposal of organic waste with the formation of a valuable energy carrier, methane. On the other hand biogas energy characterized as the best way of derive energy from polluted wastes, clean, eco-friendly, money saver, time saver, and minimizes expenditure of the foreign currency for the import of fossil fuels.

One of the most important and modern technologies, which dealing with recycling of organic wastes is Anaerobic Digestion (AD) of digestible organic waste (agricultural by-products and wastes, animal manure and slurries), which converts these substrates to renewable energy carrier (biogas), reduce the GHG, produce an excellent natural fertilizer for agriculture purposes and achievement many social and economic benefits for the producer and consumer of biogas (**Dennis and Burke, 2001**).

AD is a microbiological process of anaerobic decomposition (in the absence of oxygen) of the organic matter, which produces biogas in air-proof reactor tanks, commonly named digesters. Biogas produced in many natural environments and widely applied today. There is a wide range of micro-organisms are decomposition the organic matter in anaerobic process, which has two main end products: biogas and digestate. Biogas is a combustible gas; mainly it is a mix of methane, carbon dioxide and small amounts of other gases and trace elements. Digestate is the decomposed substrate, which rich in nutrients and suitable to be used as plant fertilizer (**Kossmann *et al.*, 1999; Kramer, 2004 and Al Seadi *et al.*, 2008**).

5.2. Current situation and potentials of biogas in Italy

Currently, the use of biomass for energy purposes contributes for just 3.5 % to the final national energy consumption (180.2 Mtoe[22]) but with a production equal to about 6.2 Mtoe, bioenergy represent 29.5 % of the whole amount of energy from renewable sources in Italy

[22] Million tons of oil equivalent

(21,1 Mtoe). The biogas contribution to the total bioenergy production is about 8 % (8.4 % of the electricity production from biomass sources) (**ENEA, 2010**).

Regional distribution of Italian biogas sector shows that, biogas plants are mainly located in the northern regions and more than 60 % are related with the agriculture and zoo-technical sector. 50 % of agriculture and zoo-technical biogas plants uses co-digestion mixture of energy crops, by-products, residues and animal manure.

According to **ENEA (2010)** could summarize the current state of biogas in Italy as follow:

- Biogas production in 2009 was about 0. 499 Mtoe;
- 78 % of biogas production coms from MSW[23] Landfills (228 plants);
- 451 plants feed by a mixture of different substrates (from agroindustry, agro-zoo-technical residues and sewage sludge);
- The total installed capacity is about 507.7 MW (including landfills);
- A recent growing trend of biogas sector comes from the growing of the agro-industrial and zoo-technical biogas production.

If we sum all quantities of energy crops (over set-aside lands) plus agricultural residues, livestock manure, agroindustry residues, MSW and sewage sludge, we could roughly estimate a potential of about 65 million m^3 / year of feedstock available for biogas production (**CRPA, 2011**).

A total of 1.3 million m^3 of biogas / day can be produced only from livestock manure that could result in a total biomethane production of 237 million m^3 / year which is about 10 times more than the actual needs of methane used for transports in Italy (**CRPA, 2011**).

5.3. Objective of the study

Due to continued rapid growth of the Italian biogas sector during the last years and for improving the exploitation of the Italian potentials of biogas production from on-farm production of energy crops and livestock manure feedstock to meet the growing demand of energy, there is a need to address the following problems:

[23] Municipal solid waste

- Farm size (different farm scales) and farm structure (on-farm crops and livestock distribution and production) suitable for establish on-farm biogas system to cover the on-farm thermal and electrical energy requirements;
- Selection of appropriate technology from different technologies of anaerobic digestion, biogas production and use, for applying at different farm scales with different farm structures.

As previously mentioned there are many mathematical models processing the different biogas problems and improving the biogas production, but there is a need to develop a mathematical model to reconcile between farm size, farm structure and on-farm biogas systems technologies applied to support selection and applying of appropriate biogas technology at any farm under Italian conditions.

The objective of this study is enhancing the exploitation of the available Italian potentials of biogas production from on-farm production of energy crops and livestock manure feedstock by develop a mathematical model RAF integrates with MAD[24] model for optimize the following on-farm variables, related to anaerobic digestion and biogas production and use:

- Allocated surface areas, distribution and production of different on-farm crops under different farm sizes (scales) (optimum data of MAD);
- Number of on-farm LSU[25] (from different available types of farm livestock) (optimum data of MAD);
- Key design elements of on-farm biogas production system (directs and helps to select the suitable technologies of on-farm biogas system) (optimum data of RAF);
- On-farm labor requirements (optimum data of RAF and MAD);
- The total net income of farm (optimum data of RAF and MAD).

[24] MAD is a bio-economical model aimed to optimize resources of a farm holding (surfaces, livestock, labor, etc.) to approach an objective function aimed to maximize net income.

[25] Livestock unit

5.3.1. Description of RAF model

The outlines of RAF model could be summarized as following:

1. RAF is a bio-energetic descriptive model in terms of sets of equations (or inequalities) run by uses GAMS code and GUI (Graphical Use Interface) works under MATLAB environment for optimize the objective function (Z) (optimization the total net income of farm for whole period which is considered by analysis);
2. RAF model support Integrated Farm Management (IFM) by enhancing economical, social and environmental sustainability of farm production;
3. RAF model support decision maker, engineers and farmers;
4. RAF model investigates the possibilities of establish on-farm biogas system (different anaerobic digestion (AD) technologies proposed for different scales of farms in terms of energy requirements) for reduce the dependence on fossil fuels and recycling the agricultural and animal by-products for produce energy and digestate (bio-fertilizers);
5. The output data of optimization process presents a preliminary design of on-farm biogas production system which contains the key design elements (*e.g.* dimensions, quantities, capacities of main components of on-farm biogas production system);
6. The output data of optimization process could be presented in form of recommendations for the best investment in energy from different on-farm potentials under different farm sizes (scales).

5.4. Main results of the study

For apply the RAF model and extracting the results, hypothetical case studies based on realistic values have been developed.

5.4.1. Case study (A)

Farm undergo to north Italy conditions (climate and slope) and oriented to conventional agriculture (non-organic) and livestock production (dairy cattle). Farm gets actual subsidies and the period considered by analysis is 10 years.

The main products of farm are field crops yield (food, feed and energy crops) and livestock products (main products: milk and meat, and by-product: manure).

The farm planning to establish an on-farm biogas system depends on co-digestion of energy crops and animal manure slurry for meets on-farm requirements of energy, moreover produce digestate (bio-fertilizers) for meets the on-farm requirements of fertilizers.

Farm structure can be defined as follows:

- Total surface area of farm is 50 ha;
- Allocated surface area for field crops cultivation is 35 ha;
- Allocated surface area for forage crops (medica, frumento-duro & altre-foraggere) is 20 ha;
- Allocated surface area for energy crops (alfalfa, maize & sorghum) is 15 ha;
- Surface area of natural surface (meadow) is 15 ha;
- Number of livestock units is 50 dairy cows;
- Market price of electrical energy is 0.25 euro / kWh_{el}.

According to the results of optimization process could give the following recommendations of biogas technology apply for case study (A):

- Recommend use the wet anaerobic digestion process with mesophilic continuous system equipped with completely stirred tank reactor (CSTR) integrates with pumping system equipped with positive displacement pumps (progressing cavity pumps), suitable for co-digestion process for feedstock contains high content of silage with animal manure slurry;
- Recommend use on-farm CHP unit of biogas with electrical capacity (ecp) 50 kWh_{el}.
- The total costs (fixed and variable) of on-farm biogas system are 336081 Euro (33608.1 Euro / year), while the total net income of on-farm biogas system is 201924.3 Euro (20192.4 Euro / year) during span life (10 years), presents 60 % of the total costs of on-farm biogas system.

5.4.2. Case study (B)

Farm undergo to north Italy conditions (climate and slope) and oriented to conventional agriculture (non-organic) and livestock co-breeding production (meat cattle and pigs). Farm gets actual subsidies and the period considered by analysis is 10 years.

The Main products of farm are field crops yield (food, feed and energy crops), tree crops yield (wood) and livestock products (main product: meat and by-product: manure).

The farm planning to establish an on-farm biogas system depends on co-digestion of energy crops and animal manure slurry for meets on-farm requirements of energy, moreover produce digestate (bio-fertilizers) for meets the on-farm requirements of fertilizers.

Farm structure can be defined as follows:

- Total surface area of farm is 50 ha;
- Allocated surface area for field crops cultivation is 45 ha;
- Allocated surface area for forage crops (medica, altre-foragger & frumento-duro) is 35 ha;
- Allocated surface area for energy crops (alfalfa, maize & sorghum) is 10 ha;
- Allocated surface area for trees (wood) is 5 ha;
- Numbers of livestock units are 150 meat calf & 200 pig;
- Market price of electrical energy is 0.25 euro / kWh_{el}.

According to the results of optimization process could give the following recommendations of biogas technology apply for case study (B):

- Recommend use the wet anaerobic digestion process with continuous system equipped with plug flow digester integrates with pumping system equipped centrifugal (rotating) pumps, suitable for co-digestion process for feedstock contains relative low content of silage with animal manure slurry;
- Recommend use on-farm CHP unit of biogas with electrical capacity (ecp) 50 kWh_{el};
- The total costs (fixed and variable) of on-farm biogas system are 359635.7 Euro (45963.6 Euro / year), while the total net income of on-farm biogas system is 325587.3

Euro (32558.7 Euro / year) during span life, presents 90 % of the total costs of on-farm biogas system.

5.5. Conclusion

The main results of this study refers to the possibility of enhancing the exploitation of the available Italian potentials of biogas production from on-farm production of energy crops and livestock manure feedstock by using the developed mathematical model RAF integrates with MAD model for optimize the objective function (Z) (optimization the total net income of farm for whole period which is considered by analysis) and presents reliable reconcile between farm size, farm structure and on-farm biogas systems technologies applied to support selection, applying and operating of appropriate biogas technology at any farm under Italian conditions.

Also the main results indicates to the flexibility and ability of RAF model to offers reliable Key design elements[26] (preliminary design) of on-farm biogas production system, which includes:

- Dilution ratio of substrate required for biogas production;
- Total quantity of diluted substrate input to digester;
- Inner-surface area of bunker silo for storage fresh silage for livestock feeding and biogas production;
- Inner-volume and inner-surface area of manure slurry tank or lagoon;
- Discharge of pumping and mixing unit;
- Inner-volume of digestion chamber;
- Inner-surface area of digester;
- Inner-volume of biogas storage chamber (low-pressure biogas tight membranes with dome shape);
- Total inner-volume of digester;
- Specific gas yield;
- Digestion chamber loading, based on the daily mass of TS input to digestion chamber;
- Digestion chamber loading, based on the daily mass of VS input to digestion chamber;

[26] Some references refer to key design elements as “design criteria”

- Biogas peak production;
- Gasholder capacity;
- Ratio of the digester volume to gasholder capacity;
- Inner-volume and inner-surface area of digestate tank;
- Allocated surface area for on-farm biogas system;
- Total on-farm biogas yield;
- Total on-farm thermal energy consumed;
- Total on-farm electrical energy consumed;
- Total net productive capacity of thermal energy from on-farm CHP unit of biogas;
- Surplus thermal energy produced from on-farm CHP unit of biogas;
- Total net productive capacity of electrical energy from on-farm CHP unit of biogas;
- Surplus electrical energy produced from on-farm CHP unit of biogas, which available for sell to the national electrical network;
- Total net income of on-farm biogas production in year t, based on electrical energy production from on-farm CHP unit.

The accurate description, calculation and optimization of this above mentioned Key design elements are the crucial factor to selection, applying and operating of appropriate biogas technology at any farm under Italian conditions.

6
RECOMMENDATIONS

6. RECOMMENDATIONS

6.1. Case study (A)

According to the results of optimization process could give the following recommendations of biogas technology apply for case study (A):

- Recommend use the wet anaerobic digestion process with mesophilic continuous system equipped with completely stirred tank reactor (CSTR) integrates with pumping system equipped with positive displacement pumps (progressing cavity pumps), suitable for co-digestion process for feedstock contains high content of silage with animal manure slurry;
- Recommend use on-farm CHP unit of biogas with electrical capacity (ecp) 50 kWh_{el}.
- The total costs (fixed and variable) of on-farm biogas system are 336081 Euro (33608.1 Euro / year), while the total net income of on-farm biogas system is 201924.3 Euro (20192.4 Euro / year) during span life (10 years), presents 60 % of the total costs of on-farm biogas system.

6.2. Case study (B)

According to the results of optimization process could give the following recommendations of biogas technology apply for case study (B):

- Recommend use the wet anaerobic digestion process with continuous system equipped with plug flow digester integrates with pumping system equipped centrifugal (rotating) pumps, suitable for co-digestion process for feedstock contains relative low content of silage with animal manure slurry;
- Recommend use on-farm CHP unit of biogas with electrical capacity (ecp) 50 kWh_{el};
- The total costs (fixed and variable) of on-farm biogas system are 359635.7 Euro (45963.6 Euro / year), while the total net income of on-farm biogas system is 325587.3 Euro (32558.7 Euro / year) during span life, presents 90 % of the total costs of on-farm biogas system.

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APPENDICES

8. APPENDICES

Table 8.1: Surface area required per livestock unit for different on-farm breeding and production facilities (paved or concrete surface) (author elaboration *cited in* **Wand and Doris, 2011**)

zo[27]	**alu_{zo} (ha / lsu)**[28]
Dairy cattle	0.002
Non-dairy cattle	0.0012
Buffaloes	0.0012
Pigs	0.0005

[27] Zoo index

[28] Surface area required per livestock unit for different breeding and production facilities

Table 8.2: Nutrition required for livestock unit in terms of diet nutrients (author elaboration *cited in* **Belloin, 1988; Stewart *et al.,* 2005 and Hall *et al.,* 2009**)

	$Fdz_{zo,di}$ [29]	
zo	**(fu[30] / lsu . year)**	**(cp[31] / lsu . year)**
Dairy cattle	3000	760
Non-dairy cattle	2000	420
Buffaloes	2000	420
Pigs	425	110

[29] Nutrition required for livestock unit in terms of diet nutrients, based on dry matter content
[30] fu = Forage unit, is a forage value of 1 kg of barley (unit)
[31] cp = Crude protein (kg)

Table 8.3: Available nutrition for livestock from on-farm production of forage crops (author elaboration *cited in* **Balliette, 1998 and Strohbehn and Loy, 2007**)

	$fds_{cz,di}$ [32]	
cz[33]	**fu / ton**	**pr / ton**
Alfalfa	210	175
Maize	150	90
Sorghum	220	83

[32] Nutrients content of forage crops available for animal feeding in terms of diet nutrients, based on dry matter content

[33] Forage crop index

Table 8.4: Nutrition purchased for livestock from market (author elaboration *cited in* **Balliette, 1998 and Strohbehn and Loy, 2007**)

	$fdm_{cm,di}$[34]	
cm[35]	**fu / ton**	**pr / ton**
Alfalfa	210	175
Maize	150	90
Sorghum	220	83

[34] Nutrients content of diet feedstock purchased from market for livestock feeding in terms of diet nutrients, based on dry matter content

[35] Market diet index

Table 8.5: Thermal energy required for warming different greenhouse areas in Italy (author elaboration *cited in* **Campiotti *et al.,* 2011**)

Climate area	**eth (kWh_{th} / ha . year)[36]**
South	14375
Middle	21750
North	26250
West coast	10000

[36] Thermal energy required for greenhouses warming

Table 8.6: Thermal energy required for livestock unit (author elaboration *cited in* **Hörndahl, 2008**)

zo	**etl_{zo} (kWh_{th} / lsu . year)[37]**
Dairy cattle	700
Non-dairy cattle	500
Buffaloes	500
Pigs	150

[37] Thermal energy required for livestock unit

Table 8.7: Electrical energy required for different greenhouse areas in Italy (author elaboration *cited in* **Campiotti *et al.,* 2011**)

climate area	**eeh (kWh_{el} / ha . year)[38]**
South	16000
Middle	11000
North	9000
West coast	26000

[38] Electrical energy required for greenhouses

Table 8.8: Electrical energy required for livestock unit (author elaboration *cited in* **Commercial Energy Advisor, 2008**)

zo	**eel_{zo} (kWh_{el} / lsu . year)**[39]
Dairy cattle	1000
Non-dairy cattle	550
Buffaloes	550
Pigs	95

[39] Electrical energy required for livestock unit

Table 8.9: Total number of workers required for operate on-farm biogas system (author elaboration *cited in* **Lovrenčec, 2010**)

EET (kWh_{el} / year)[40]	**lre (worker / kWh_{el})**[41]
2^{6}	5^{-7}

[40] Total net productive capacity of electrical energy from on-farm CHP unit of biogas

[41] Number of workers required for biogas system in terms of workers required for produced electrical energy unit

Table 8.10: Total mass of on-farm fresh silage available for livestock feeding and biogas production (author elaboration *cited in* **Kaiser *et al.*, 2004 and Mickan, 2006**)

cz[42]	**MSF_{cz} (ton / ha. year)**[43]	**ce**[44]	**MSG_{ce} (ton / ha. year)**[45]
Alfalfa	50	Alfalfa	50
Maize	40	Maize	40
Sorghum	40	Sorghum	40

[42] Silage crop index for livestock feeding
[43] Mass of fresh silage from different on-farm crops available for livestock feeding
[44] Energy crop index
[45] Mass of fresh silage from different on-farm crops available for biogas production

Table 8.11: Mass of on-farm manure slurry available for biogas production (author elaboration *cited in* **Dong *et al.*, 2006**)

zo	**alm_{zo} (kg of lsu mass / lsu)**[46]	**sme_{zo} (kg of manure slurry / kg of lsu mass . day)**[47]
Dairy cattle	600	0.106
Non-dairy cattle	450	0.106
Buffaloes	450	0.106
Pigs	150	0.08

[46] Average live mass of livestock unit
[47] Average specific mass of excrements

Table 8.12: Mass of TS for air-dried silage and manure slurry (author elaboration *cited in* **Mickan, 2006 and Al Seadi *et al.*, 2008**)

ce	**tss_{ce} (ton / m^3)[48]**	**zo**	**tsm_{zo} (ton / m^3)[49]**
Alfalfa	0.200	Dairy cattle	0.100
Maize	0.192	Non-dairy cattle	0.100
Sorghum	0.192	Buffaloes	0.100
		Pigs	0.080

[48] Mass of TS for air-dried silage
[49] Mass of TS for manure slurry

Table 8.13: Concentration of TS in unmixed substrate (air-dried silage or manure slurry only) (author elaboration *cited in* **Mickan, 2006 and Al Seadi *et al.*, 2008**)

Feedstock	**Its (%)[50]**
Air-dried silage	
Alfalfa	77
Maize	74
Sorghum	74
Manure slurry	
Dairy cattle	10
Non-dairy cattle	10
Buffaloes	10
Pigs	8

[50] Concentration of TS

Table 8.14: Biogas yield generated, based on biogas yield per mass unit of fresh silage from energy crops (author elaboration *cited in* **NNFCC, 2009 and Hopwood, 2011**)

ce	**gyc_{ce} (m^3 / ton)[51]**
Alfalfa	185
Maize	220
Sorghum	200

[51] Biogas yield generated from surface area unit of energy crops

Table 8.15: Biogas yield generated, based on biogas yield per livestock unit (author elaboration *cited in* **NNFCC, 2010**)

zo	**gyl_{zo} (m^3 / lsu . year)[52]**
Dairy cattle	580
Non-dairy cattle	435
Buffaloes	435
Pigs	110

[52] Biogas yield generated from livestock unit

Table 8.16: Thermal stages and typical hydraulic retention times (author elaboration *cited in* **Al Seadi *et al.*, 2008**)

sy[53]	**Process temperatures (°C)**	**hrt_{sy} (day)**[54]
Psychrophilic	< 20	80
Mesophilic	From 30 to 42	40
Thermophilic	From 43 to 55	20

[53] System index
[54] Hydraulic retention time

Table 8.17: Specific gas yield (author elaboration *cited in* **Biogas Process for Sustainable Development, 1992**)

sy	**sgy (m^3 of biogas / m^3 of total inner-volume of digester. day)[55]**
Psychrophilic	≤ 0.2
Mesophilic	From 0.2 to 0.4
Thermophilic	From 0.4 to 0.6

[55] Specific gas yield

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