# Economical analysis of energy recovery from the aerobic bioconversion of solid urban waste organic fraction

**Valentina Gorietti, Francesco Di Maria, Manuel Benavoli, Mirco Zoppitelli**

Università degli Studi di Perugia, Facoltà di Ingegneria,

Dipartimento di Ingegneria Industriale, Italy

**Abstract**

In this paper, the aerobic treatment of the organic fraction of Solid Urban Waste, performed in a biocell plant with the possibility of recovering heat for civil or industrial needs, was examined from the economical point of view. Using a thermodynamic theoretical model, an evaluation of the thermal recoverable energy from the biological process of waste treatment and a proposal for a real plant were done. A compression heat pump is utilized for the production of sanitary hot water. The entire process is optimized on a fraction of the entire mass of waste treated in a existing plant in Umbria necessary to cover the thermal requirements of the buildings around the plant. The most significant physical and economical results and the layout of the plant are represented and discussed.

**Keywords**

Aerobic treatment, organic fraction, biocell, energy recovery, heat pump, economical analysis.

# 1 Introduction

Waste management is of the utmost importance for many countries, especially highly developed ones, due to implications it entails. One of the main problems is represented by the composition of SUW (DI MARIA AND PAVESI, 2005;FANTOZZI ET AL.,2002); it contains different substances that have to be treated in a special way, to attain an acceptable environmental protection level. The organic fraction is particularly reactive and if disposed in sanitary landfills, without previous adequate treatments, a large amount of dangerous and pollutant substances can be produced (DESIDERI ET AL.,2003). Some waste treatments can also present a chance to produce other by-products like energy, recycled materials and other products with both economical and environmental benefits. Different solution have been proposed to reduce the risk arising from such organic fraction (DI MARIA AND SAETTA, 2004; DI MARIA ET AL., 2003; ADANO ET AL., 2004) even if the more suitable and diffuses techniques still remain aerobic degradation of the organic content before its final disposal. In fact, this solution represent higher efficiency in organic carbon reduction, if compared to other treatments (i.e. anaerobic) (TUSSEAU-VUILLEMIN ET AL., 2003), and less complicated plant requirements. Furthermore, the gas production is represented mainly by $CO_2$ and vapour. Nonetheless, the aerobic reduction of the organic carbon content produces a substance, known as compost, that in some cases can be exploited in agriculture to improve quality of soil. Another aspect of the aerobic treatment is represented by the large amount of heat generated during the decomposition process (THEMELIS AND KIM, 2002; BIZUCOJC AND LEDAKOWICZ, 2003); this causes an increase in organic fraction temperature which positively relates to disinfestations from the more diffuses pathogen bacteria. The temperature level is maintained under 70-75°C, generally about 55-65°C, to avoid biological process inhibition, with the help of high thermal loss mainly due to convection and heat mass transfer by the large amount of fresh air necessary to supply oxygen to aerobic bacteria. Anyway it is possible to built a special plant to reduce thermal loss and to introduce an adequate amount of air, in which the excess heat can be extracted in a different way, by a thermal machine. In such a way it is possible to recover energy from the process. The system proposed in this paper consist of a bioconversion cell (THEMELIS AND KIM, 2002), in which the aerobic bioconversion of the SUW organic fraction takes place, coupled with a heat pump to extract excess heat. A thermodynamic model was implemented to simulate the system's behaviour and performances. By varying some main system parameters, both biological and energy recovery process were analyzed and discussed. A layout for the realization of the bioconversion system was proposed, in order to evaluate the economical benefits of the heat recovery and its utilization for thermal needs of the surrounding buildings.

**Table 1** Nomenclature

| ***Symbols*** | | ***Subscripts*** | |
|---|---|---|---|
| *BOD* | Biological Oxygen Demand | *air* | Air |
| *C* | Oxidized to total OF ratio | *d* | Dry |
| *C* | Specific Heat | *el* | Electrical |
| $CH_4$ | Methane | *ev* | Evaporated |
| $CO_2$ | Carbon dioxide | *in* | Input |
| *COP* | Coefficient Of Performance | *ins* | Insulate |
| $c_p$ | Specific heat constant pressure | *OF* | Organic Fraction |
| *H* | Vapour enthalpy | *out* | Out |
| *HP* | Heat Pump | *ox* | Oxidized |
| *K* | Convection heat exchange coefficient | *pr* | Produced |
| *OF* | Organic Fraction | *re* | Reinjected |
| *OM* | Organic Matter | *real* | Real |
| *M* | Mass | *s* | Stoichiometric |
| *Q* | Heat power | *t* | Time |
| *R* | Thermal resistance | *theo* | Theoretical |
| *S* | Area | *tot* | Total |
| *S* | Thickness | *w* | Water |
| *SUW* | Solid Urban Waste | *1* | Biocell walls |
| *T* | Temperature | *2* | Convection with ambient air |
| *W* | Power | *3* | Water evaporation |

| Symbols | | Subscripts | |
|---|---|---|---|
| $X$ | Specific air humidity | 4 | Injected water |
| $A$ | Excess air | 5 | Organic matter |
| $\Delta$ | Difference | | |
| $\Lambda$ | Thermal conductivity | | |
| $M$ | Real to theoretical COP ratio | | |
| $\dot{m}$ | Mass rate | | |

# 2 Model description and main assumptions

The proposed plant is plotted in Figure 1. The biocell is delimitated by concrete walls parallelepiped volume inside of which the organic fraction is stored. The walls can be insulated to reduce heat loss during the process. The biomass occupies about 70% of the whole available volume, to allow for water injection and air circulation vessels. The oxygen required by the process is introduced in the biocell by the ambient air that is fan pumped under the organic fraction supported by a grid system. In this preliminary analysis the energy necessary to pump air was neglected. The air circuit can operate in the following ways:

1. open way, by the continuous introduction of fresh ambient air;
2. closed way, by the circulation of the same rate more times.

A water injection system is necessary to keep organic fraction humidity around 50-60% by mass. The water is pumped and injected on the top of the moisture and then recovered and, to reduce water consumption, circulated back from the bottom of the biocell.

The organic fraction temperature during the process can be controlled both by the rate of injected air or by the heat extracted by a heat pump. In the second case it is possible, as shown in the following, to maximize the HP heat extraction operating in close way, related to air injection system. The analysis of the system was performed by implementing a simulation code able to take into account both the biological process and the HP characteristic. In order to do this, some assumptions were made for each system component.

## 2.1 Biological process

The SUW organic fraction consists mainly of food and paper waste; known the mass fraction of each component, it is possible to establish the chemical composition of the organic fraction (THEMELIS AND KIM, 2002)(Tab. 2). The molecular formula of the considered substance has been established (1), where the chemical components with lower mass fraction (i.e. N and S) were neglected.

$$C_6H_{10}O_4 \quad (1)$$

The aerobic bioconversion of the organic substances can be considered as an oxidation process with main by-products as carbon dioxide, water and heat. Considering the reaction (2), exploiting the heat of formation of each reactant and product, it is possible to estimate that the amount of heat released per mole of oxidised organic substances is about 616 kcal.

$$(C_6H_{10}O_4)_x + 6.5O_2 = (C_6H_{10}O_4)_{x-1} + 6CO_2 + 5H_2O + 616kcal \qquad (2)$$

Starting from equation (2), the stoichiometric air, required by the process, is about 6,9 kg per kg of organic substance. Anyway, to allow a better oxidation process and temperature control, higher amounts of air are introduced in the biocell. This is expressed by parameter "α" given by the ratio of the introduced air mass rate related to the stoichiometric one (3).

$$\alpha = \frac{\dot{m}_{air}}{\dot{m}_{air,s}} \qquad (3)$$

Another important aspect to consider is the rate at which the oxidative reaction takes place. According to the available models proposed in literature (KEENER ET AL., 1998) the amount of oxidised to total oxidizable mass ratio is related to time and temperature as shown in (4).

$$c_t = 1 - e^{-(0.00632 \cdot 1.066^{(T-20)}) \cdot t} \quad [kg_{ox} / kg_{tot}] \qquad (4)$$

The time required for a complete oxidation process is theoretically infinite; considering that real aerobic treatments requires generally 15-20 days, computation were halted when the amount of bio converted organic fraction resulted to be no less than 80%.

## 2.2 Thermal loss

The biological process produces heat that causes an increase of the whole mass temperature; this has to be kept under 55-65°C, so the heat generated inside the biocell system has to be dissipated to avoid excessive temperature increase. The heat transfer process can be summarized in the main following:

1. Heat transfer by the biocell walls;
2. Heat exchanged by the process ambient air;
3. Heat absorbed by water evaporation;
4. Heat exchanged by injected water;
5. Heat absorbed by the OF.

Considering the mean temperature levels, the heat exchanged by irradiation was neglected. Referring to the figure 1, it is possible to note that the heat exchanged by the biocell walls is due both to the hot organic fraction mass, (5), and the heated air occupying the internal volume at the biocell top (6).

$$R_{OF} = \frac{1}{\frac{1}{K_{OF}} + \frac{s_{conc}}{\lambda_{conc}} + \frac{s_{ins}}{\lambda_{ins}} + \frac{1}{K_{air}}} \quad [m^2K/W] \tag{5}$$

$$R_{air} = \frac{1}{\frac{1}{K_{air}} + \frac{s_{conc}}{\lambda_{conc}} + \frac{s_{ins}}{\lambda_{ins}} + \frac{1}{K_{air}}} \quad [m^2K/W] \tag{6}$$

The global heat exchanged in this first way is given by (7).

$$Q_1 = R_{OF} \cdot S_{OF} \cdot \Delta T + R_{air} \cdot S_{air} \cdot \Delta T \quad [kW] \tag{7}$$

The second and third heat exchange process happen contemporary (8) and are represented by the one that occurs between the organic fraction mass and the process air.

$$Q_2 + Q_3 = \dot{m}_{air,d} \cdot c_p \cdot \Delta T + \dot{m}_{air,d} \cdot (X_{out} \cdot T_{out} + X_{in} \cdot T_{in}) \tag{8}$$

The ambient air, injected from the bottom of the biocell, passes through the hot organic fraction extracting heat both in convective than in evaporative way. In particular the humidity evaporation process, that causes ambient air saturation at rising temperature, is the one that involves the higher amount of extracted heat. The fourth heat exchange considered process concerns to the need of keeping the organic fraction humidity quite constant during the whole treatment (9).

$$Q_4 = \dot{m}_w \cdot C_w \cdot \Delta T \tag{9}$$

The water injected can produce a mass temperature reduction due to water lower temperature value. If this occurs a fraction of the heat produced by the biological process is absorbed by the injected water. The final heat exchange process considered regards the heat absorbed by the organic fraction itself, during the starting period or due to some mass temperature reduction that can occur in different process phases (10).

$$Q_5 = M_{OF} \cdot C_{OF} \cdot \Delta T \tag{10}$$

The whole heat exchanged is quantified as the sum of the different heat exchange process before mentioned (11).

$$Q_{tot} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \quad [kW] \tag{11}$$

## 2.3 Heat pump

The heat pump represent the second important component of the proposed plant. In fact this system has to provide heat extraction in particular system operating conditions, and to release this heat for different user demands. Due to the temperature levels and to the achievable performances, a vapour compression heat pump was chosen. The HP behaviour was simulated defining the theoretical Coefficient Of Performance (12).

$$COP_{teo} = \frac{T_{out}}{T_{out} - T_{in}} = \frac{Q_{out}}{W_{el,in}} \tag{12}$$

To evaluate more realistic plant performances, the theoretical COP was corrected by the aid of an empiric coefficient μ, (13), that was estimated considering the theoretical and real COP for a wide range of real heat pumps available on the market, of similar size, to the one exploited in the present analysis.

$$\mu = \frac{COP_{real}}{COP_{theo}} \tag{13}$$

When simulating the system behaviour evaluation in different operating conditions, some assumption were made for main system parameters. Heat exchange evaluation is possible only if the geometry and the components of the biocell are defined (Tab.3) and if ambient air inlet condition are assumed (Tab. 4). The possibility of recovering heat are influenced both on biocell operating condition and by the heat pump features (Tab.5). In particular, related to the HP, heat loss due to hot fluid transport inside dedicates piper and minimum temperature difference, between the hot organic fraction and the HP operating fluid, have been assumed.

# 3 Real system description

## 3.1 Plant layout

The plant is made up of 19 biocells, the handling system for the compost, the hydraulic system and the HP group; the layout scheme is shown in figure 2.

### 3.1.1 Biocells

The biocells are realized in reinforced concrete, with internal dimensions summarized in table 3 and wall thickness of 0,4 m; the profile is shown in figure 1. There is an access on the upper side to allow the insertion of biomass and another lateral one for the extraction of the compost. The biocells are formed into two line ( of 9 and 10 biocells side by side) in specular position with the lateral access one in front of the other one. By containing the heat loss, the biocells are laid for half of their height, while the exposed to air surface is insulated with 3 cm of pugging; the internal surfaces are waterproofed to avoid the penetration of the sludge produced during the biodegradation process.

### 3.1.2 Handling system

The screened and crushed MSW organic fraction can be loaded onto the biocell, through the upper access, using a conveyor belt. The trapezoidal conformation of the ground and the two internal rotating augers, driven by an electric engine, allow an uniform biomass distribution. The rotating augers are utilized at the end of the biological process to void the biocells on a conveyor belt situated between the two line of biocells and destined to the collecting point.

### 3.1.3 Hydraulic system and HP group

The biocells have some circuits for the realization and monitoring of the biological process and heat recovery: a ventilation system, an irrigation system, sludge collection canalizations and a heat recovery system. The ventilation system is formed by perforated ducts on the bottom of the biocell, a fan, an air inlet and an air recirculation system. In this way it’s possible a complete change of air in the fixed days and recirculation in the others. The irrigation system is located in the internal upper side of the biocell and connected through a recirculation system to the sludge collection canalizations on the bottom of the biocell under a biomass detainment grid; the irrigation takes place partially with grid water and the rest with sludge recirculation. The heat recovery system is realized with pipes passing through the biomass and a circulation pump; the water gets warm reaching temperature value next to the biomass one. This circuit ends with an upstream heat exchanger (η=99%); here the water coming from biocells heats the grid water, or the user one, heading for the HP group. The HP group has 4 vapour compression heat pumps (450 kWt each one); this, electrical driven, increases the water temperature till the needed one for sanitary uses or domestic heating (75-85°C). By varying valves position, a partialization of the HP group is possible; in this way the performance isn’t penalised and the needs of the users can be satisfied.

## 3.2 Main energetic results

The proposed system can be introduced in a existing MSW integrated treatment system of a macroarea of the entire MSW management system of Regione Umbria. The daily quantity of organic fraction treated has been estimated in about 30 ton/day.

The permanence time of the organic material into the biocell necessary to obtain the nearly complete degradation is about 19 days; in figure 4 temperature and bio converted fraction trend of the organic fraction during the biological process are shown. At the end of the process the bio converted fraction is about 85% and the temperature 60°C. Using a theoretical an excess air of 9 and 5 complete change of air during the process period. By hypothesizing a continuous working of the system, loading each day a single biocell and considering the previously discussed system characteristic, the proposed system will be composed of 19 biocells (table 6). An evaluation of the process was done calculating the thermal loss for a single biocell through the walls, exchanged by the process ambient air, absorbed by water evaporation, exchanged by injected water and absorbed by OF. The ambient air absorbs heat from the system through the three ways previously described; from the graph (figure 5) is clear that the main contribution to the heat loss is the water evaporation. More than 85% of the water loss in that process is restored by irrigation, while the remaining 15% in part by fresh air and in part is produced directly by the biological process. These kind of losses are present only in the complete air change days; in the other days, recirculation days, the air is saturated and thermal equilibrated with the system. During that days the loss Q1, Q2 and Q3 are absent and the heat can be entirely recovered. The recoverable heat from the biocell can be used as input of a heat pump. In table 5 are summarized the characteristic of a generic HP available on the market. In figure 6 are shown the recoverable heat, available heat (equal to the recoverable one minus the loss), out heat and electric consumption of the HP; the heat recoverable from a single biocell, and so the one produced by the HP, decreases during the biological process. Whereas, those values are constant for the entire system composed of 19 biocells (table7).

# 4 Economical analysis

An economical analysis of the described system was done to evaluate the size and the trend of the investment. To that end realization ($I_0$), operating (CE), maintenance (CM) and staff costs (CP) and profits from heat recovery (RE) were analysed.

The realization costs consist in: excavation work for the positioning of the biocells, biocells, rotating augers and respective engines, hydraulic ventilation systems, pumps and fans, heat exchanger, heat pumps, control system, handling systems. The realization costs are estimated in 2.000.000 €.

The operating costs are due to the electrical energy consumption of the many device of the plant; these costs have been evaluated assuming 180 day/year of work. For work time of 24 hours for the fans for the air recirculation, 8 hours for handling system (each day only one loading cycle for a single biocell), 10 hours for the HP group, an electrical consumption of nearly 775 MWh was estimated. Referring to the actual medium rate of electrical energy in Italy (0,13 €/kWh), the operating costs amount, on the average, to 100.000 €/years.

The maintenance and staff (2-3 units for shift) costs have been estimated in 100.000 €/year and 60.000 €/year respectively.

The hot water production for thermal-sanitary utilization using the HP allows an economic saving, in addition to the energetic one, compared with the same production using a traditional gas boiler. Referring to the actual medium rate of methane gas in Italy (0,05 €/kWh), the recovery of nearly 2900 thermal MWh from the biological process of waste treatment represents a profit of 150.000 €/year.

All the values until now are summarized in tables 8, 9 and 10.

The net present value (NPV) at the j-th year can be expressed as:

$$NPV = -I_0 + \sum_{j(1)}^{n} \frac{FC}{(1+i)^j} \tag{13}$$

Where the cash flow FC is:

$$FC = -CE - CP - CM + RE \tag{14}$$

The economic analysis was done on a time interval of 20 years; with a discount rate *i* of 6% the trend of the investment during the plant life-time was valued (figure 7). The plant costs can't be covered only by the profit resulting from the heat recovery. For this reason, the annual due D resulting from the waste disposal taxes paid from the user, necessary for the depreciation of the investment in n years, was calculated as follow:

$$D(n) = -FC + \frac{NPV_n - I_0}{\sum_{j=1}^{n} \frac{1}{(1+i)^j}} \tag{15}$$

A period of 5 and 10 years for the depreciation of the investment was taken. A range of 0,04÷0,06 €/kWh$_t$ for methane gas and of 0,08÷0,16 €/kwh$_{el}$ for electric energy rate was considered. In table 9 the results for three different combinations of that costs are summarized. The most profitable combination is A (highest kWh$_t$ rate, lowest kWh$_{el}$ rate); with these assumption the annual due D ranges from 505.000 to 639.000 €/year for depreciation in 5 years and from 314.000 to 383.000 €/year in 10 years. In figure 8 is shown the investment trend. The annual waste disposal fees was calculated considering an utilization of the plant of 180 day/year and 30 ton/day of treated biomass; these fees range from 96 to 118 €/ton for 5 years depreciation and from 58 to 81 €/ton for 10 years.

# 5 Conclusion

The aerobic bioconversion of the Solid Urban Waste organic fraction is one of the most suitable solution for such waste treatment, before final disposal, mainly due to its simplicity and efficiency in reducing pollutant effect on the environment. Anyway, by the aid of the plant proposed in this work, it is possible to couple the bioconversion process with the energy recovery one. In fact, the heat released by the aerobic bacteria activity, generally at 55-65°C, can be exploited by a heat pump and increased both in quality, achieving about 80-90°C, than in quantity, achieving about 4000-5000 kJ per kg of treated organic fraction. This heat, produced as hot water, can be utilised for thermal needs of the nearby users allowing economic and emissions savings ( $CO_2$ reduction, compared to a traditional methane gas boiler, of 31,3 %). This economic savings and waste disposal taxes paid from the user, permit a depreciation of the investment for the realization (2.000.000 €) and operating (mean cost 115.000 €/year) of the plant in a short period. An economic evaluation of the investment was done; by supposing a discount rate of 6%, the annual disposal taxes amounts to 109 €/ton on the average for a depreciation time of 5 years, and 71 €/ton for 10 years.

**Table 2** Ultimate analysis of MSW organic fraction. (% by weight)

| Component | C [%] | H [%] | O [%] | N [%] | S [%] |
|---|---|---|---|---|---|
| Mixed food wastes | 48 | 6,4 | 37,6 | 2,6 | 0,4 |
| Fruit wastes | 48,5 | 6,2 | 39,5 | 1,4 | 0,2 |
| Meat wastes | 59,6 | 9,4 | 24,7 | 1,2 | 0,2 |
| Mixed paper | 43,4 | 5,8 | 44,3 | 0,3 | 0,2 |
| Yard wastes | 50,1 | 6,4 | 42,3 | 0,1 | 0,1 |

**Table 3** Biocell geometry and organic fraction feature.

| | | |
|---|---|---|
| Length | 4 | [m] |
| Width | 5 | [m] |
| High | 2,5 | [m] |
| Wall thickness | 0,2 | [m] |
| Insulate thickness | 0,03 | [m] |
| Internal volume | 50 | [$m^3$] |
| Filling factor | 0,75 | |
| Moisture volume | 37,5 | [$m^3$] |
| Moisture water content | 64 | [%] |
| Moisture weight | 30000 | [kg] |

**Table 4** Ambient air feature

| | | |
|---|---|---|
| Pressure | 101325 | [Pa] |
| Temperature | 15 | [°C] |
| Relative humidity | 50 | [%] |

**Table 5** HP main feature

| | | |
|---|---|---|
| $COP_{real}$ / $COP_{theoric}$ | 40 | [%] |
| COP | 4,8 | |
| Heat loss | 5 | [%] |
| $\Delta T$ loss | 5 | [°C] |
| $\Delta T_{HP}$ | 30 | [°C] |

**Table 6** Biological process parameters.

| | |
|---|---|
| Daily treated MSW | 30 ton |
| Process duration | 19 days |
| Biocells number | 19 |
| Excess air | 9 |
| Air recirculation days | 1° – 3° – 8° – 13° – 18° |

**Table 7** Medium energy production.

| | | |
|---|---|---|
| Produced Heat | $1{,}7 \times 10^8$ | kJ/day |
| Recoverable heat | $1{,}2 \times 10^8$ | kJ/day |
| Available heat | $1{,}1 \times 10^8$ | kJ/day |
| HP produced heat | $1{,}4 \times 10^8$ | kJ/day |
| Electrical power consumption | $2{,}98 \times 10^7$ | kJel/day |

**Table 8** Economical analysis parameter.

| | |
|---|---|
| Realization costs | 2.000.000 € |
| Discount rate | 6% |
| Plant duration | 20 years |

**Table 9** Energetic consumption and production.

| | *Electric consumption [kW]* | *Usage [h/day]* | *Consumption [kWh]* |
|---|---|---|---|
| Rotating augers | 50 | 8 | 72000 |
| Fan | 19 | 24 | 82080 |
| HP (e.e.) | 345 | 10 | 621000 |
| | *Available Power [kW]* | *Usage [h/day]* | *Production [kWh]* |
| HP (heat) | 1656 | 10 | 2980800 |

**Table 10** Economical analysis summary

| | Annual cost [€/year] | | |
|---|---|---|---|
| | A<br>0,08€ / $kWh_{EL}$<br>0,06 € / $kWh_T$ | B<br>0,13 € / $kWh_{EL}$<br>0,05 € / $kWh_T$ | C<br>0,16 € / $kWh_{EL}$<br>0,04 € / $kWh_T$ |
| Operating costs | -62006 | -100760 | -124012 |
| Profits from heat recovery | 178848 | 149040 | 119232 |
| Maintenance costs | -100000 | -100000 | -100000 |
| Staff costs | -60000 | -60000 | -60000 |
| Annual FC | -43158 | -111720 | -164780 |
| D(5) | 517881 | 586454 | 639526 |
| D(10) | 314824 | 383397 | 436469 |
| Annual waste disposal taxes(5) [€/ton ] | 96 | 109 | 118 |
| Annual waste disposal taxes(10) [€/ton ] | 58 | 71 | 81 |

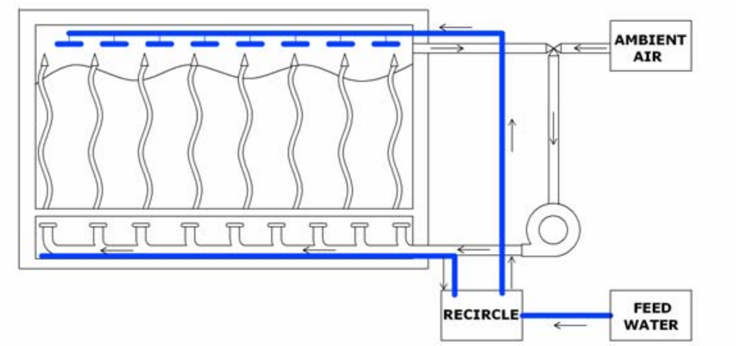


**Figure 1.** Biocell with heat pump schematic

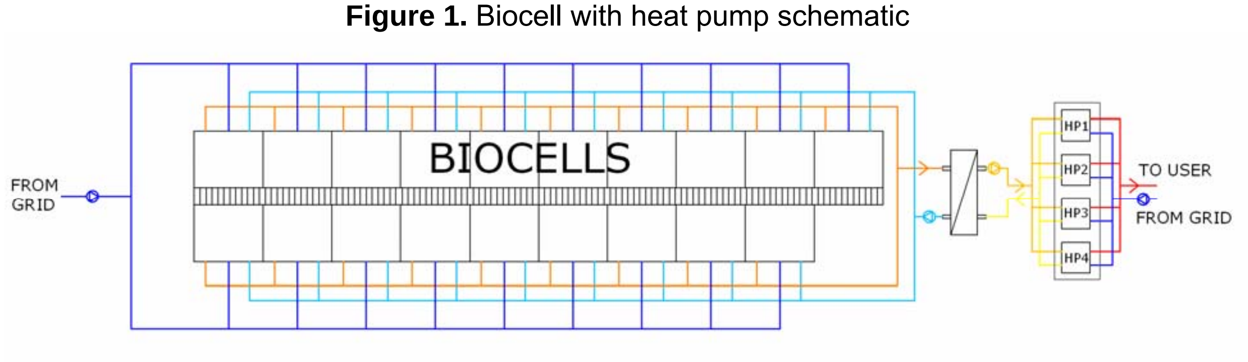


**Figure 2.** Layout of the plant.

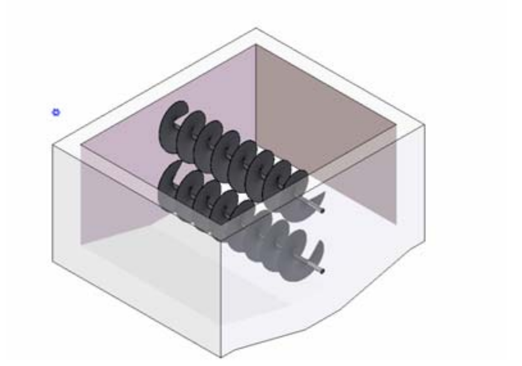

**Figure 3.** Three-dimensional view of a biocell.

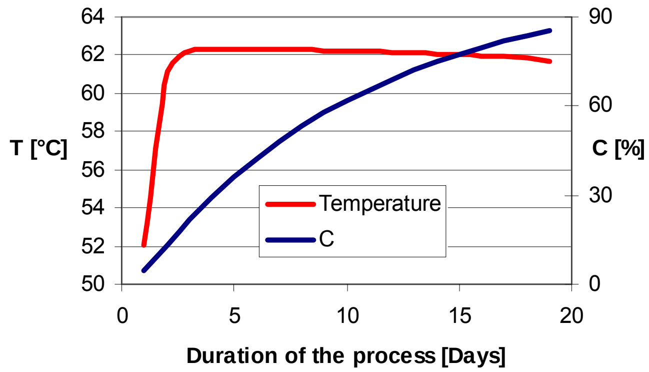


**Figure 4.** Bio converted fraction and temperature of the organic fraction versus time.

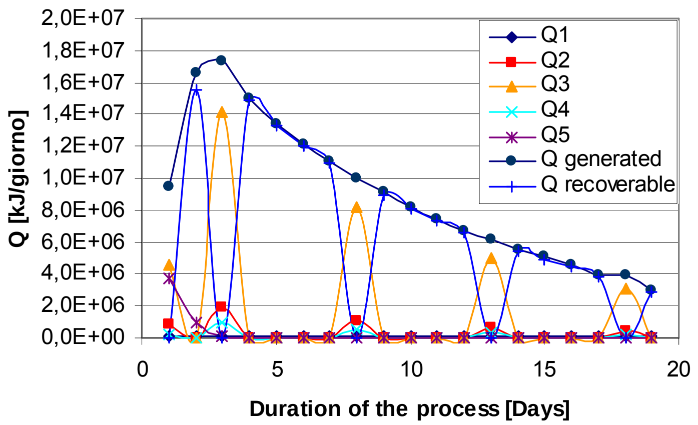


**Figure 5.** Thermal losses, heat generated and recoverable versus time.

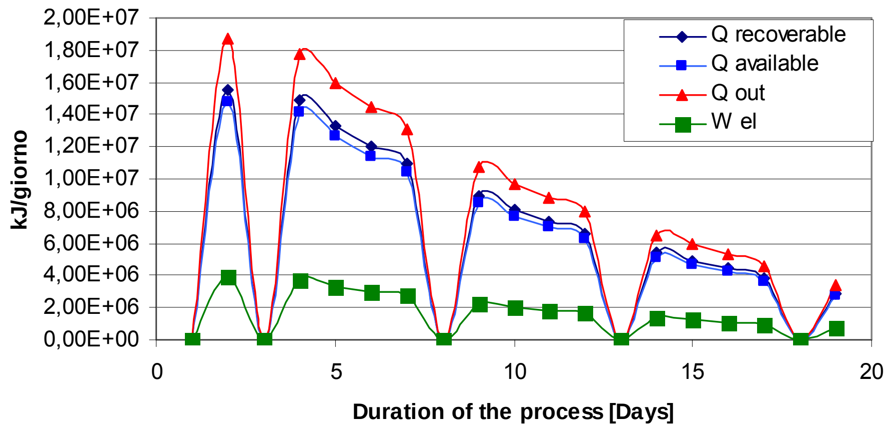


**Figure 6.** Heat recoverable, available, produced and electrical energy absorbed versus time.

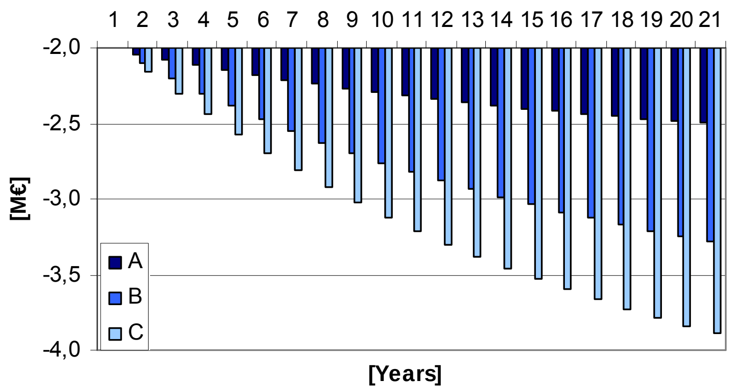


**Figure 7.** Investment trend

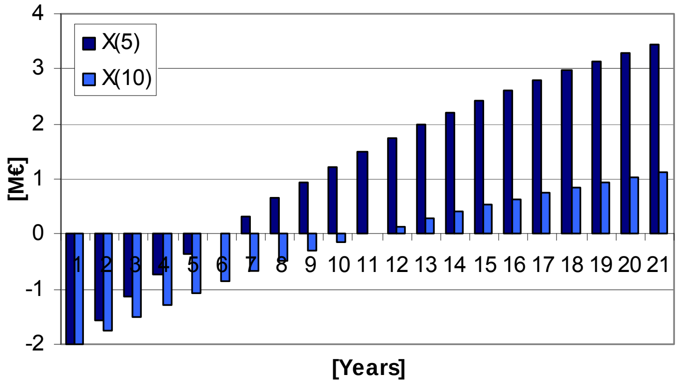


**Figure 8.** Investment trend with 5 and 10 years depreciation.

# 6 Literature


| | | |
|---|---|---|
| Adani, F., Tambone, F., Gotti, A. | 2004 | ”Biostabilization of municipal solid waste”, *Waste Management*, Vol. 24, Issue 8, pp. 775-783. |
| Desideri, U., Di Maria, F., Leonardi, D., Proietti, S. | 2003 | "Sanitary landfill energetic potential analysis: a real case study", *Energy conversion and management*, Vol. 44 Issue 12, pp. 1969-1981. |
| Di Maria, F., Saetta, S. | 2000 | “Life Cycle Assessment Analysis for solid urban waste management: the case of a 100.000 inhabitants Italian town”, *The 16th International conference on solid waste technology and management,* Philadelphia, PA, December, 10-13. |
| Di Maria, F., Saetta, S., Leonardi, D. | 2003 | "Life Cycle Assessment of a PPV plant applies to an existing SUW management system", *International Journal of Energy Research,* Vol. 27, Issue 5, pp. 481-494. |
| Di Maria, F., Saetta, S. | 2004 | "Life cycle assessment for municipal solid waste management improvements: the case of a 100.000 inhabitant Italian town", *Journal of Solid Waste Technology and Management*, Vol. 30, No. 1, pp. 53-65. |
| Di Maria, F., Pavesi, G. | 2005 | “RDF to energy plant for a central Italia region SUW management system: energetic and, economical analysis”, *Applied Thermal Engineering*, accepted for publication. |

| | | |
|---|---|---|
| Keener, H., M., Elwell, D., L., et al. | 1998 | "Specifying Design/Operating of Composition System Using Pilot Scale Data", *Applied Engineering in Agriculture,* Vol. 13, Issue 3, pp. 377-384. |
| Liwarska-Bizukojc, E., Ledakowicz, S. | 2003 | "Stoichiometry of the aerobic biodegradation of the organic fraction of municipal solid waste (MWS)", *Biodegradation*, Vol. 14, Issue 1, pp. 51-56. |
| Themelis, J., N., Kim, Y., H. | 2002 | "Material and energy balances in a large-scale aerobic bioconversion cell", *Waste Management and Research,* Vol. 20, pp. 234-242. |
| Tuesseau-Vuillemin, M., H., Dispan, J., Mouchel, J., M., Servais, P. | 2003 | "Biodegradable fraction of organic carbon estimated under oxic and anoxic conditions", *Water Research*, Vol. 37, Issue 9, pp. 2242-2247. |


**Authors' addresses**


Prof-Ing. Francesco Di Maria (1) , Ing. Valentina Gorietti (2)
Università degli Studi di Perugia
Dipartimento di Ingegneria Industriale – Sezione Macchine
Via G.Duranti 67 – 06100 Perugia - Italia
Telephone (1) +39 075 585 38 76 ; (2) +39 075 585 37 48
Email (1) fdm@unipg.it ; (2) vgorietti@mach.ing.unipg.it
Website: www.macchine.unipg.it