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Article

Collection of Thermal Energy Available from a Biogas Plant for Leachate Treatment in an Urban Landfill: A Sicilian Case Study

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Abstract: The landfill of Bellolampo is located in northern Sicily and serves the greater area of Palermo (Sicily). In the recent past, the landfill has been progressively renovated in order to align the waste disposal process with the state-of-the-art technology. During the past years, the site had been equipped with seven biogas engines, fuelled with the biogas produced at the oldest part of the landfill. More recently, another two engines of the same type have been installed for a total of 9 MW electrical power installed at the landfill. The landfill of Bellolampo faces a significant leachate disposal problem. Some 250 m^3 of contaminated leachate are produced daily and transported by ships and trucks to an area about 1000 km away before being treated and disposed. The disposal of this extremely polluting fluid causes significant nuisance in the integrated waste management process and significant disposal expenses (in excess of € 60 per ton of fluid disposed and € 4.5 mln per year). Furthermore, the recent legislation strongly suggests the landfill manager to activate fully integrated systems and 100% landfill auto-sustainability. On the other hand, the above mentioned biogas engines produce a great quantity of unused thermal energy yearly. This study demonstrates that this energy could be effectively and efficiently used to enable the sustainable in-house treatment of the leachate. The treatment is aimed to significantly reduce leachate volume in order to reduce fluid disposal costs. A thorough economical analysis is also performed. The study demonstrates that a medium sized landfill can sustainably and cost-effectively be managed through a fully integrated system thus producing substantial economies.

Keywords: landfill; leachate; evaporation; reverse osmosis; thermal energy

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1. Introduction

Waste has been for many years the focus of environmental policies at the international and European level. The EU has promoted a number of industry regulations in order to pursue environmental objectives and, at the same time, prevent possible risks to human health [1–9]. These regulations have introduced numerous innovations both in the classification of wastes and the ways adoptable for their recovery and/or disposal. For this purpose it is now widely believed that waste management policies should not rely only on the traditional form of disposal in landfills, but should also focus on integrated strategies.

However, nowadays the landfill is the main management tool in some European countries and in Italy. According to the 2010 waste report prepared by the Institute for Environmental Protection and Research, the amount of waste landfilled amounted to 44.9% [10]. With percentages of 96%–97%, in Sicily the landfill remains the only way of disposal of municipal waste [1,11].

Landfilling involves multiple negative environmental impacts on both a small and larger scale. The anaerobic fermentation of waste causes the production of polluted products in liquid (leachate) and gaseous (biogas) form, which can persist for over thirty years after closure of a landfill and require appropriate treatment or disposal [12–14].

Disposal of leachate is a major one of the most expensive in the operation of these plants [15]. For this reason, the leachate is normally treated *in situ*, as required by Italian legislation (Decree Law 36/2003 [16]), which allows confinement of concentrated leachate in the landfill.

The choice of the type of treatment is highly correlated to the experimental verification of the quantitative and qualitative characteristics of the historical data collected during the life of the landfill.

The variability of the quantitative and qualitative characteristics of the leachate and the strict limits on the amount and type of waste water manageable by treatment plants according to Italian legislation [17] require the use of cleaning techniques, which are able to guarantee low-cost and environmentally sustainable treatment of leachate.

This study evaluates the possibility of *in situ* treatment of the landfill leachate at Bellolampo, a landfill located in the homonymous district in the province of Palermo (Sicily). To date the landfill leachate is disposed of at *ad hoc* treatment sites located outside the region, with significant management costs. This study suggests treating the leachate through a chemical-physical process in order to decrease its volume and to enable the treatment at the same landfill.

Two scenarios were simulated: the first scenario foresees a two-stage vacuum evaporation and a subsequent finishing treatment by a reverse osmosis process; the second scenario considers a reverse osmosis treatment followed by a vacuum single stage evaporation of the residue retained from the osmotic membranes. In both scenarios the heat necessary for the evaporation of water is recovered from seven biogas engines installed at the landfill. The calculations shows that for each kWh_e transferred to the grid, some 1.6 kWh_t may be recovered from the engine coolant and the exhaust flue gas. This thermal energy can be used to heat the water to be used as vector fluid for evaporation.

Economical, engineering and energetic potential advantages and critical problems were evaluated for both scenarios. Investment and operating costs for the proposed technical solution were also evaluated.

2. Framework of the Study Area

Bellolampo landfill is located in northwestern Sicily, some 10 km from the historical city center of Palermo, in the Bellolampo-Piano Badami district. The area is at an altitude between 420 and 475 m above the sea level, about 400 m higher than the average altitude of the city. The area of Bellolampo is also 2 km away from two large districts with high population density (the "Borgo Nuovo" and "CEP Michelangelo" neighborhoods); the closest villages are found at about 1 km from the landfill alongside a provincial road.

The biogas energy recovery plant is located within the area of the disposal facility. The system was installed by Asja Ambiente Italia S.p.A. and is currently operated by the same company. The landfill area occupies some 600,000 m^2 of land including the area for the biogas plant which occupies an area of about 3000 m^2. Bellolampo is a hilly landfill with a significant expansion in height, and it has grown by individually compact layers. The normal set of Bellolampo landfill users consists of the metropolitan area of Palermo and about fifty other municipalities within the province of Palermo. The landfill serves over one million habitants and it is one of the largest of Southern Italy.

From a regulatory point of view, the plant disposal is categorized as a non-dangerous wastes landfill according to the Decree Law 36/2003 [16] (former landfill class I for the disposal of solid urban wastes and urban-assimilated wastes according to the resolution 27/07/1984).

3. Description of the Hypothesized Designed Solutions

The installed biogas engines are used only for the production of electric energy. However, they also produce a significant amount of heat which could be recovered to treat the leachate, by means of an evaporation process. The engines could work as cogenerators thereby allowing a considerable increase of overall energy efficiency of the plant [18–20].

The assumptions made concern *in situ* leachate treatment, by a vacuum evaporation process and a physical and chemical finishing treatment. Technologies were chosen in coordination with the landfill operator and heat recovery was evaluated following two different scenarios:

- *Scenario 1*: leachate evaporation is provided by a two stage evaporative process, performed in two different chambers. In the first chamber the leachate, warmed up to an initial temperature of 70 °C, starts evaporating at the absolute pressure of 27.08 kPa. The steam generated in the first chamber is condensed in the evaporator of the second chamber which operates at 50 °C temperature and 12.5 kPa pressure. The distillate coming from the evaporative unit is treated by reverse osmosis.
- *Scenario 2*: leachate is sent to a reverse osmosis plant, after a flocculation treatment. The retained phase of the osmosis membrane is sent to an evaporation unit where it is evaporated at controlled pressure and at 65 °C temperature. The distillate of the evaporation unit, cooled down to 25 °C, will be used for the counter-wash of osmotic membranes.

Leachate characterization data were extracted by a preliminary design of a treatment plant that was initially evaluated in the landfill and approved in 2010 by AMIA, the operator of the plant. The designed treatment plant was assumed capable of producing 250 m^3/day of treated leachate. The

characterization of the leachate was obtained from the above mentioned design and by the preliminary monitoring campaign used for the design:

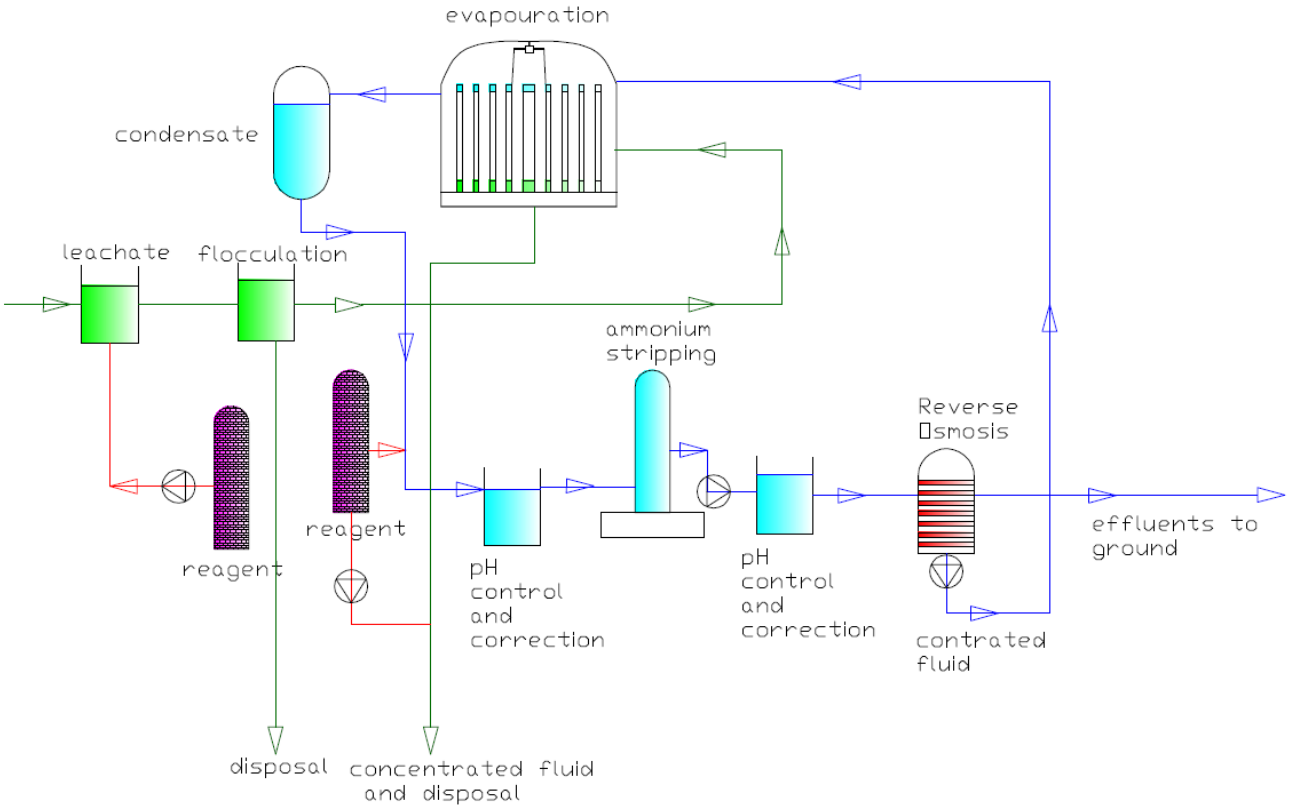
- pH, 7.5–8;
- Total suspended solids, 2000–3000 mg/L;
- BOD_5, 4000 mg/L;
- COD, 10,000 mg/L;
- Chlorides (Cl), 4000 mg/L;
- Ammonia Nitrogen (NH_4^+), 2500 mg/L;
- Phenols, 0.27 mg/L;
- Fe, 45.2 mg/L;
- Mn, 3.8 mg/L;
- Cu, 0.25 mg/L;
- Zn, 0.68 mg/L;
- Pb, 0.45 mg/L;
- Cd, 0.98 mg/L;
- Cr, 0.65 mg/L;
- Ni, 0.78 mg/L.

The first scenario, as reported in Figure 1, provides a single line of treatment consisting of:

- a unit for storage and correction of pH;
- a flocculation unit;
- six double-effect vacuum evaporators with forced circulation with a potential capacity of 50 m^3/day;
- a condensing unit equipped with an air condenser;
- a pH adjustment unit;
- a stripping unit for the absorption of ammonia from the condensate, with air-closed circuit, *i.e.*, without emission in the atmosphere;
- a pH adjustment unit;
- a reverse osmosis section with potential treatment capacity of 220 m^3/day;
- reagent storage, concentrated residue, process water.

According to this scheme, the leachate is sent to the flocculation unit after pH adjustment. The chemical precipitation process of metals is carried out following two particular stages which include the production of metal species of very low solubility and therefore capable of precipitating. The precipitation allows separation of solid/liquid phases. In the specific case the metallic ions in solution are converted into insoluble species by reaction of the metallic soluble species with specific reagents [21]. The metal concentrations are, in any case, low and they do not represent risks for the preservation of the osmosis membrane. Leachate organics are high and, as a consequence, most of the metal concentrations may be in the form complexes binding with organic substances or ammonium. In this form, the flocculation efficiency may be low, but the risk for membrane fouling is reduced accordingly. In the bound form, the metal removal is then guaranteed by the membrane treatment.

Figure 1. Unifilar diagram of the treatment plant in Scenario 1.



A flocculation process provided before the evaporation unit is used for the protection of the evaporators. The leachate treatment is provided through vacuum evaporation. Given the peculiar characteristics of the leachate, this treatment ensures a greater purification efficiency.

The evaporation unit consists of six modules capable of treating some 50 m^3/day, these modules are double-effect type and work under vacuum and forced convection and are fed with hot water at a temperature of 90 °C.

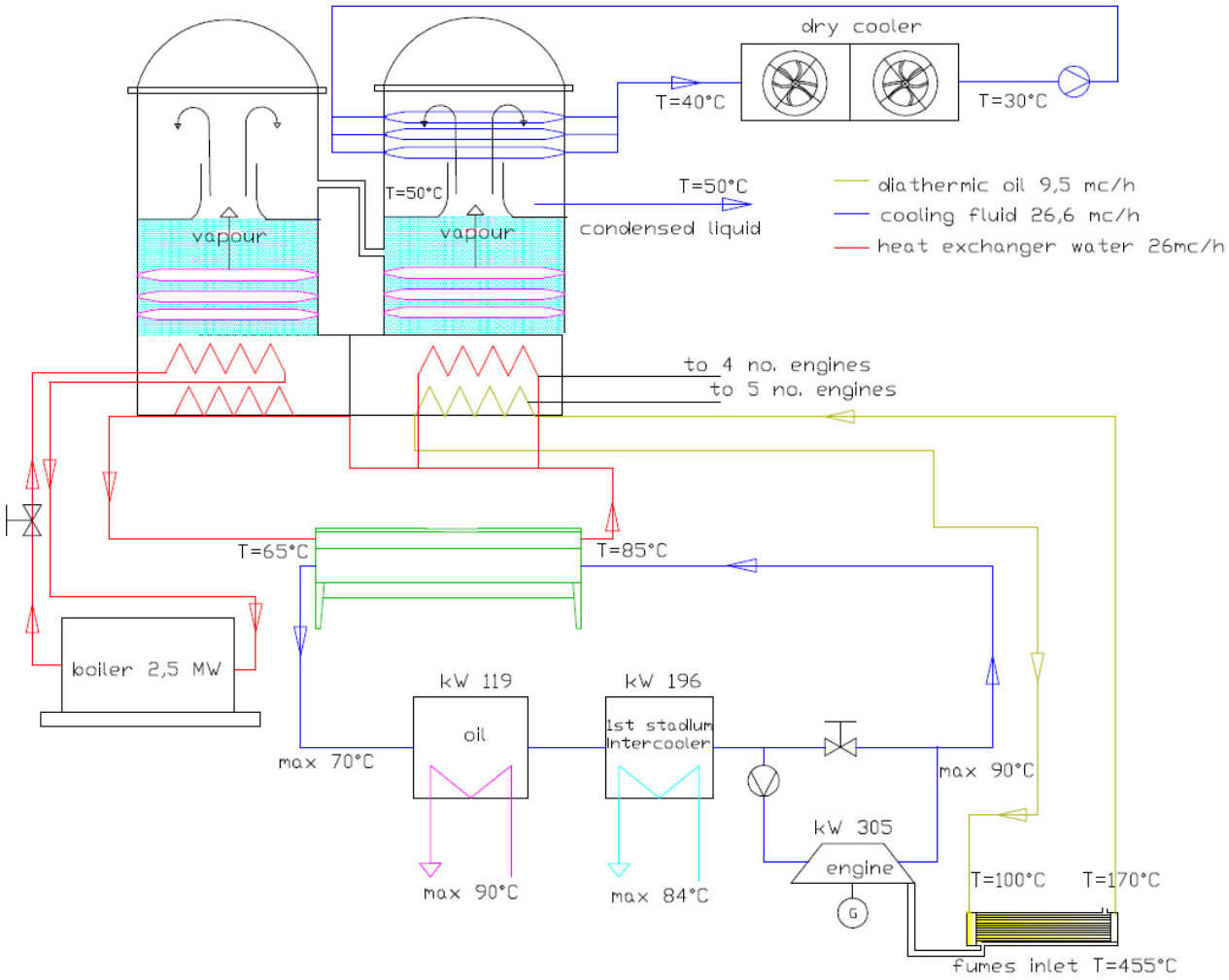
The choice of using a forced circulation system, although more costly from the energy consumption point of view, ensures low fouling of the evaporators and consequently a high operational reliability. In any case, in order to reduce the energy losses in the plant piping system, smooth and corrosion resistant pipes are used thus avoiding the growth of surface roughness that can significantly increase the wall shear stress and augment the flow resistance [22].

During the first stage, the evaporation is carried out under vacuum at an absolute pressure of 27.08 kPa and at a temperature of 70 °C. The evaporated liquid is sent to the second boiling chamber at a temperature of 50 °C and a pressure of 12.5 kPa.

The heat transferred from the evaporator is totally recovered thus generating an additional source of energy and saving on energy costs. A forced circulation of wastewater through an external tube bundle, allows heating of the waste itself which does not evaporate but only gains sensible heat; at the exit of the tube bundle, the wastewater enters the liquid/vapour separator, in which an instantaneous evaporation (isoenthalpic expansion) of the water in a quantity equivalent to the amount of sensible heat gained is carried out.

The heat supplied to the evaporators is collected from five of the seven biogas engines in the landfill. A water-water heat exchanger is used for the recovery of heat from the engine cooling circuit; while a diathermic oil–exhaust gas exchanger is used to recover heat from the exhaust flue gas. Figure 2 shows a diagram of the heat recovery set-up.

Figure 2. Unifilar diagram of the thermal power recovery plant in Scenario 1.



The engine coolant is used to cool the engine itself, the oil and the first intercooler stage. The flow of coolant is assumed to be 26.6 m^3/h as reported in engine data sheets, the calculated recoverable power is approximately 620 kW.

The water flow rate of the heat exchanger plates is obtainable by the following formula:

$$\dot{m} = \frac{\dot{Q}}{C_p \times \Delta T} \quad (1)$$

where $\dot{Q}$ is the thermal power recovered; C_p is the vector fluid coefficient at constant pressure account; ΔT is the fluid's temperature change.

Considering water as the vector fluid, we may assume the following: $\dot{Q}_a$ = 620 kW; C_p = 4.186 kJ/kg·K; ΔT = 85 − 65 = 20 °C. The water mass flow was equal to $\dot{m}$ = 26.6 m^3/h. Similar

assumptions are made for the recovery of heat power from the engines' exhaust flue-gases which are cooled down from 455 °C to 180 °C. The mass flow of diathermic oil is equal to $\dot{m} = 9.5$ m^3/h.

The thermal power required to increase the leachate temperature can be calculated assuming a 18 °C initial temperature and a $\dot{m}_p = 9.35$ m^3/h leachate mass flow to reach the desired final temperature equal to $T_f = 70$ °C. The calculated thermal power is $\dot{Q}_n = m_p C_p \Delta T = 631$ kW.

The leachate pre-heating process must be performed within the same evaporators, so as to avoid the evaporation of volatile compounds to the atmosphere. The energy needed to evaporate a kilogram of leachate is equal to $\dot{Q}_p = 1350$ kJ/kg.

The total thermal power recoverable from the engines is calculated as the sum of the power collected from cooled exhaust gas at 180 °C and the thermal power of the four cooling circuits corrected for the efficiency of the respective heat exchangers:

$$\dot{Q}_r = \sum_{i=1}^{n=5} \eta_o \dot{Q}_0 + \sum_{i=1}^{n=4} \eta_a \dot{Q}_a - \dot{Q}_n = 4091 \text{ kW} \tag{2}$$

where η_o and η_a are the heat exchangers' yields, equal to 0.65 for the oil-exhaust gas exchanger and 0.9 for the water-water exchanger. The power needed is that required to increase the leachate temperature from 18 °C to 70 °C.

The enthalpy supplied to each kilogram of leachate is calculated by dividing the thermal power recoverable to the mass flow of the leachate itself, all reduced by 10% for the losses due to heat exchange with the water carrier fluid:

$$Q_r = \frac{0.9\ \dot{Q}_r}{\dot{m}_p} = 1269.62 \text{ kJ/kg} \tag{3}$$

The percentage of the evaporated fluid will be equal to the ratio between the recovered energy and the energy provided for the phase change:

$$\frac{Q_r}{Q_p} = 94\% \tag{4}$$

The treatment by evaporation yields the following mass balance:

- 250 m^3/day of leachate to treat;
- 237 m^3/day of treated effluent;
- 13 m^3/day of concentrate.

To cover the thermal needs of the evaporation process even in the case of a partial plant stoppage for routine or extraordinary maintenance of engines, the installation of a natural gas boiler is also provided.

Three of the evaporators will be connected to the engines and other two will be connected to both the engines and the boiler.

In case of an engines' partial stop, the boiler will provide the extra energy for leachate evaporation. The boiler power is 1.5 MW. A sixth evaporator starts working during maintenance on other

evaporators. This way a constant amount of leachate treatment is ensured. A number of additional silos will be provided to store the leachate in case the biogas plant is stopped completely.

The distillate coming out of the evaporation section is sent to a pH measurement and control bath equipped with a stirrer and pH meter operating at a 50 °C temperature. A membrane metering pump, installed inside the bath, is used also to add sodium hydroxide (NaOH) used as a reagent to vary the distillate pH.

Depending on the quantity of leachate to be treated and the quality required for the waste water (disposal on land according to the Table 4 of the Decree Law 152/06 [17]), the use of an ammonia stripping system may be necessary, in a closed air and absorption circuit. All the condensate (coming out the evaporator and conveyed in the pH correction bath) is fed to the ammonia treatment section.

Stripping and absorbing of the gaseous flow are carried out in a closed circuit, thus avoiding any problem related to any gas emissions to the atmosphere. The ammonia transferred from the liquid phase to the gas phase during stripping is absorbed, (in acidic solution) before the subsequent reuse of air in the stripping tower. The biphasic contact between the liquid phase containing ammonia and the stripping air then occurs in the stripping tower. The gaseous stream leaving the stripping column is sent to an absorbent tower where the ammonia is transferred to an acidic phase for the production of ammonium sulphate.

The distillate leaving the stripping unit must be cooled down in order to continue with the further finishing treatment before being discharged to the ground. Distillate cooling is provided by an air heat exchanger, as the evaporative towers may not be used due to the high temperatures reached in summer and to the presence of dust in the atmosphere. In order to avoid any problems with the osmotic membrane, the condenser outlet temperature should not exceed 25–30 °C.

The distillate leaving the evaporator is then subjected to a reverse osmosis treatment. The system consists of a pre-treatment pump, a high pressure pump, one or more pressure tanks, control systems and instrumentation.

In order to overcome the natural osmotic pressure, a high pressure pump increases the water pressure through a membrane, this way the fluid is divided in an effectively pure fluid (permeate) and in a process fluid (retained fluid). Water molecules pass through the membrane while the contaminants are removed from the membrane and come out as waste.

Each of the pressurised cylinders may contain one or more spiral shaped membranes used for the reverse osmosis process. The proposed reverse osmosis treatment allows obtaining the following mass balance:

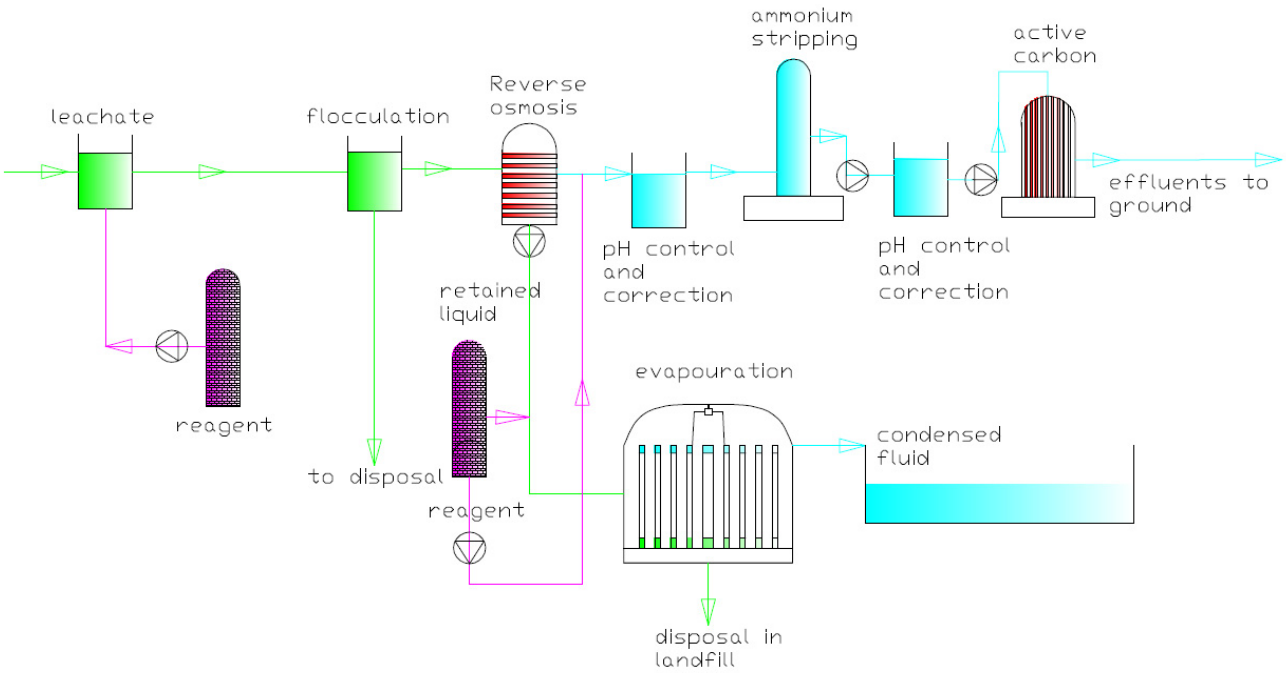
- Inlet flow, about 220 m^3/day;
- Outlet flow 154 m^3/day (70% of the inlet flow);
- Concentrate 66 m^3/day (30% of the inlet flow).

Plant effluent may be disposed of in a nearby area called Vallone Celona, by means of a pumping system or be reused in compliance with the limits imposed by the Legislative Decree 152/06 [17]. The concentrate (retained fluid) coming out from the reverse osmosis unit will be fed back to the top of the evaporation unit. The concentrated fluid leaving the evaporation unit will be disposed of through appropriate facilities as required by Decree law 36/2003 [16].

With regard to Scenario 2 the design data are assumed to be equal to those of the previous scenario. The design of the plant in question (see Figure 3) covers one line of treatment consisting of:

- a storage and pH adjustment unit;
- a flocculation unit used for separation of metals;
- a 250 m^3/day reverse osmosis unit;
- a unit for pH adjustments;
- a stripping unit for ammonia absorption, equipped with a closed air circuit to avoid any emissions to the atmosphere;
- a unit for pH adjustments;
- an activated carbon adsorption unit;
- three 50 m^3/day mono-effect evaporators with forced circulation;
- an air condenser unit for cooling down the condensate;
- a condensate collection unit used for backwashing of the membranes.

Figure 3. Unifilar diagram for the treatment plant in Scenario 2.



The metal chemical precipitation process is the same as used in the previous scenario; the operation of the flocculation process before the reverse osmosis treatment is important to protect the membranes. In this second case the leachate treatment is carried out by means of reverse osmosis. This treatment allows separating water from leachate through a selective barrier (the membrane itself) which allows the passage of water while it has very low (or negligible) permeability to other substances. The type of membrane will be chosen taking into account the characteristic of the fluid to be treated.

The use of membranes for leachate treatment causes problems affecting the membranes life, mainly related to fouling [15]. Fouling of the membranes is caused by suspended substances, microorganisms, oily and greasy substances, as well as precipitation of salts due to their excessive concentration; fouling occurs especially with traditional, spiral wound type membranes, which hampers cleaning with the traditional washing techniques, thus causing frequent membrane replacements. For these reasons, flat type membranes are to be preferred for leachate treatment.

Flat membranes may be arranged on different levels separated by discs, hence being easily replaceable in case of damage and easy to clean. The installation of this type of membranes provides higher efficiency, due to the high overall membrane exchange surface, and a more economic operation [21]. Moreover, fouling of the membranes may be further limited by leachate sand filtration or an ultra-filtration system [15].

Mass balance for the present scenario reads as follows:

- 250 m^3/day of leachate to treat;
- 150 m^3/day of treated effluent;
- 100 m^3/day of concentrate.

The permeate from the reverse osmosis unit is sent to the pH adjustment system and to the ammonia stripping unit in order to remove ammonia nitrogen, to limit its concentration to the values indicated by current legislation. The ammonia stripping system is the same as the one provided in the previous scenario.

Prior to its disposal on the ground, the permeate is sent to the activated carbon adsorption unit for the elimination of any phenols present in the water. The filter bed is made of a layer of high porosity and very high active surface activated carbon. These properties give the material the necessary adsorption power. The particle size of activated carbon is studied in order to favour the kinetics of the adsorption mechanisms, thus allowing optimization of the required contact time.

One or more layers of inert materials (quarz sand) with a fixed particle size and layer height are installed under the filter bed. Two 10 m^3/h tanks containing activated carbon are provided for the specific plant.

Evaporation is carried out keeping the retained fluid at 65 °C and to the pressure of 25.05 kPa. The evaporation unit is made up of three modules, each capable of processing 50 m^3/day, of the mono-effect type and operating under a forced circulation regime. The high amount of retained fluid is reduced by an evaporation process.

The materials used for the plant are of the scraped surface type and salt and acid corrosion resistant. Evaporation of the saturated aqueous solution starts as soon as the solution is heated by the preheaters. The necessary heat is collected from the exhaust flue-gases from the biogas engines. Figure 4 shows a diagram of the thermal power recovery plant.

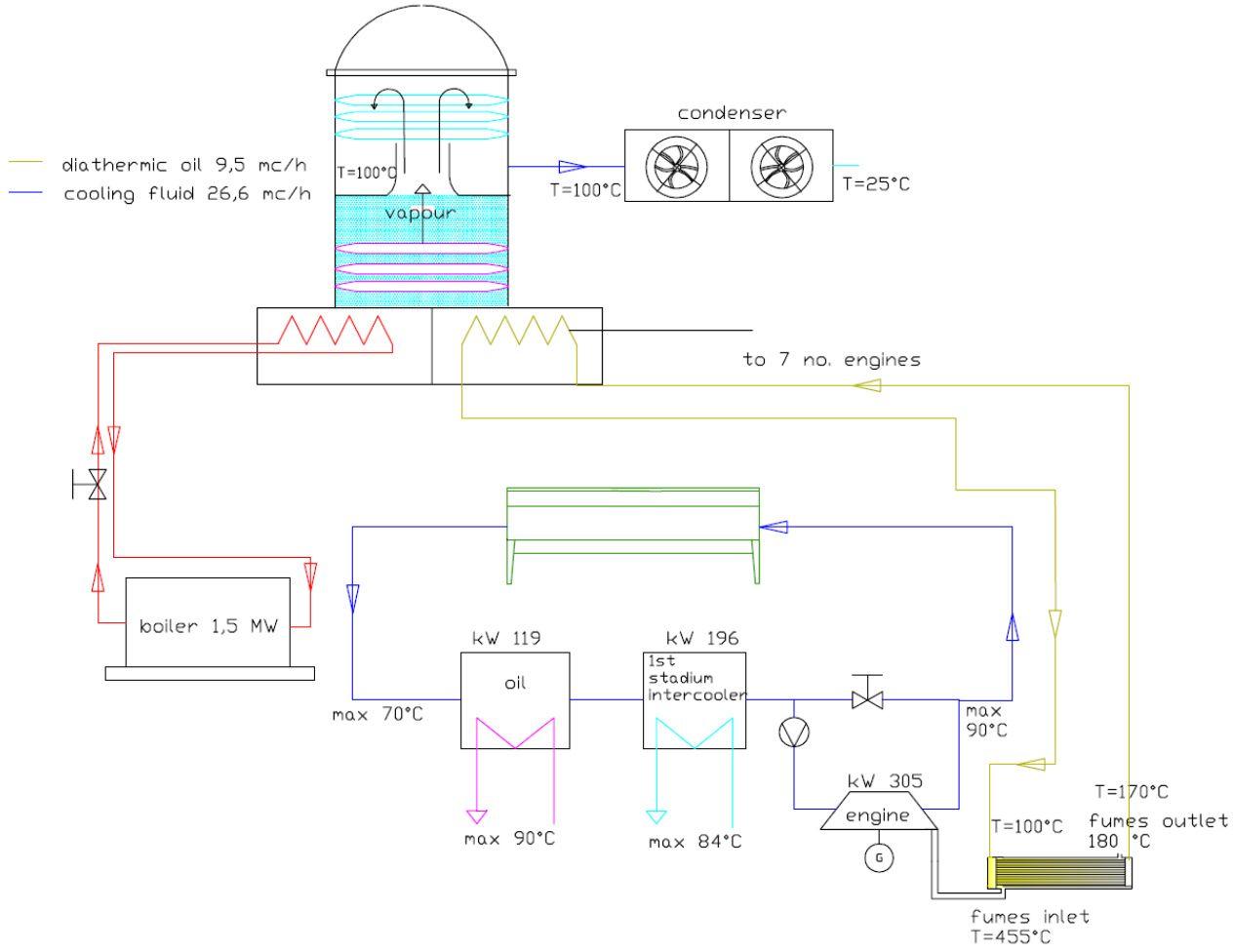
In this scenario, a single stage oil-fumes exchanger from five of the seven engines is used. The system is used for vaporisation of the retained fluid coming from the osmotic membranes. This fluid is approximately half of the incoming leachate.

The retained fluid arriving from the reverse osmosis section at a temperature of approximately 18 °C is warmed up to a temperature of 65 °C. The power to be supplied is equal to:

$$\dot{Q} = \dot{m} \times c_p \times \Delta T = 226.25\,\text{kW} \tag{5}$$

where $\dot{m}$ = 1.15 kg/s is the mass flow of the retained fluid; c_p = 4.186 kJ/kg K; $\Delta T = 65 - 18 = 47$ °C.

Figure 4. Unifilar diagram of the thermal power recovery plant in Scenario 2.



The recoverable power is equal to:

$$\dot{Q}_r = \sum_{i=1}^{n=5} \eta \times \dot{Q}_0 - \dot{Q} = 2263.75\,\text{kW} \tag{6}$$

where η = 0.65 is the yield of the tube bundle heat exchanger; $\dot{Q}_0$ = 498 kW is the power recoverable from the exhaust gases; $\dot{Q}$ = 226.25 kW is the power to take the solution to saturated liquid.

The evaporation enthalpy at atmospheric pressure and at the temperature of 65 °C is equal to h_{lv} = 2346.2 kJ/kg. Thus the percentage of evaporated fluid will be:

$$X = \frac{0.9\,\dot{Q}_r}{\dot{m} \times h_{lv}} = 0.75 \tag{7}$$

As in the previous case, the recoverable power is reduced by 10% due to the heat losses with the water carrier fluid. The evaporation process presents the following mass balance:

- retained fluid 100 m^3/day;
- 75 m^3/day of distillate;
- 25 m^3/day of concentrate.

The distillate coming out from the evaporation unit is cooled down by air-cooled condenser and accumulated in special concrete tanks, and then used as backwashing water for the osmotic membranes. A series of submersible pumps enables the process. As in the previous scenario, a methane fuelled boiler is connected to an evaporator. In this case the boiler thermal power is 1000 kW.

4. Economic Analysis

The economic analysis of the system is performed as a decision making tool to support the decision maker. A comparison between the current situation and the two scenarios is also carried out. Table 1 shows the current situation, in particular with regards to the costs of disposal per liter of leachate and the total annual cost for disposal of the 75,000 m^3 annual average amount of leachate. These values are derived from historical landfill data.

Table 1. Current situation.

Disposed product	**Current scenario**
Production (peak)	250,000 liters/day
Current cost for disposal	0.06 €/liter
Average annual cost for disposal(for a quantity of 75.000 m^3/year)	4,500,000 €

An "investment" and "operational" cost analysis was performed for the proposed plant. Table 2 shows the investment costs amortized over ten years and the operative costs which include the electric energy consumption for the operation of the evaporators and the membranes and the plant ordinary maintenance costs.

Table 2. Costs analysis Scenario 1.

Type of costs	**Scenario 1**
Cost of the investment	3,500,000 €
Depreciation	350,000 €
Hourly consumption of the evaporator kW + dry cooler	75 kWh
Hourly cost per kW	0.08 €/kWh
Energetic cost per hour	30 €/h
Osmosis plant power	27 kW
Hourly cost per kW	0.08 €/kWh
Energetic cost per hour	2.16 €/h
Total Energetic cost per hour	32.16 €/h
Concentrate disposal cost	234,000 €/year
Maintenance cost + chemicals	130,000 €/ year
Total annual cost of the treatment	2,555,472 €/ year
Annual savings	**1,944,528 €/ year**

Costs were estimated from the preliminary design of the treatment plant and from the relevant literature [23].

The total annual cost of the first scenario includes the consumption of electricity, the plant maintenance costs, reagent costs, disposal of the concentrate and the thermal energy supplied by the

company that operates the biogas plant [24]. The latter was assumed in 0.04 eurocents per kilowatt hour of energy supplied for 85 °C hot water.

The same reasoning has been developed for the second scenario. Table 3 shows the corresponding investment and operational costs. As a final analysis, the specific costs including depreciation were calculated and compared with the current situation. Values are shown on Table 4. Using comparable energetic costs, Table 4 shows how the second scenario is the most economically convenient alternative due to investment and maintenance costs.

Table 3. Costs analysis Scenario 2.

Type of costs	**Scenario 1**
Cost of the investment	3,000,000 €
Depreciation	300,000 €
Hourly consumption of the evaporator kW	75 kWh
Hourly cost per kW	0.08 €/kWh
Energetic cost per hour	18 €/h
Osmosis plant power	180 kW
Hourly cost per kW	0.08 €/kWh
Energetic cost per hour	14.4 €/h
Total Energetic cost per hour	32.4 €/h
Maintenance cost + chemicals	70,000 €/ year
Concentrate disposal cost	450,000 €/year
Total annual cost of the treatment	1,773,280 €/ year
Annual savings	**2,726,720 €/year**

Table 4. Specific costs for the proposed scenarios.

Specific costs (€/m^3)	**Current Situation (€/m^3)**	**Scenario 1 (€/m^3)**	**Scenario 2 (€/m^3)**
Depreciation	-	4.67	4
Total energetic costs	-	3.09	3.11
Maintenance cost + chemicals	-	1.73	0.93
Cost of the concentrate disposal	-	3.12	6
Cost of thermal energy	-	15	10
Total cost of the treatment	60	34.07	23.64
Savings	**-**	**25.93**	**36.36**

5. Conclusions

Due to the strict limits set by the law on wastewater treatment plants, conventional depuration systems are not the most efficient treatments for landfill leachate, Thus, innovative techniques capable of ensuring economically and environmentally sustainable systems are required. This study performs a preliminary assessment of the economic and technical feasibility of leachate treatment at Bellolampo, a landfill located in the province of Palermo, Italy.

Two technically feasible scenarios have been assumed, based on a physical-chemical approach treatment; both scenarios involve the design of an integrated treatment system capable of producing a discharge fluid compatible with the limits enforced by Decree Law 152/06. Results show that both

scenarios comply with the table limits for discharge to the soil under existing legislation. Both scenarios envisage a leachate volume reduction by means of an evaporation process. The related costs are kept low thanks to heat recovery from a set of biogas engines installed at the plant premises.

Results highlight the most economically convenient scenario, in relation to the investment and operational costs as well as reliability of the process. This study shows that leachate disposal costs, normally one of the major cost items in landfill management, can be reduced by more than 50% through the use of appropriate innovative treatments. In this case, the presence of a biogas plant allows significant energy recovery, thus significantly contributing to reduce the operating costs of the plants.

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References

1. Messineo, A.; Panno, D. Municipal waste management in Sicily: Practices and challenges. *Waste Manag.* **2008**, *28*, 1201–1208.
2. Kinnaman, T.C. The economics of municipal solid waste management. *Waste Manag.* **2009**, *29*, 2615–2617.
3. Antizar-Ladislao, B.; Turrion-Gomez, J.L. Decentralized energy from waste systems. *Energies* **2010**, *3*, 194–205.
4. Messineo, A.; Marchese, F. Performance evaluation of hybrid RO/MEE systems powered by a WTE plant. *Desalination* **2008**, *229*, 82–93.
5. Butterworth, W.R. The technology of waste, biofuels and global warming in viable closed loop, sustainable operations. *Energies* **2009**, *2*, 1192–1200.
6. Asdrubali, F.; Cotana, F.; Messineo, A. On the evaluation of solar greenhouses efficiency in building simulation during the heating period. *Energies* **2012**, *5*, 1864–1880.
7. Goh, Y.R.; Zakaria, R.; Yang, Y.B.; Nasserzadeh, V.; Swithenbank, J. Reduction of NO_x during incineration of municipal solid waste by a fundamental combustion technique. *J. Inst. Energy* **2003**, *76*, 72–79.
8. Marvuglia, A.; Messineo, A. Monitoring of wind farms' power curves using machine learning techniques. *Appl. Energy* **2012**, *98*, 574–583.
9. Yang, Y.B.; Goh, Y.R., Zakaria, R.; Nasserzadeh, V.; Swithenbank, J. Mathematical modelling of MSW incineration on a travelling bed. *Waste Manag.* **2002**, *22*, 369–380.
10. *Rapporto Rifiuti Urbani*; Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA): Rome, Italy, 2010; ISBN: 978-88-448-0430-5.
11. Sicilian Environmental Protection Agency (ARPA). Available online: http://www.arpa.sicilia.it (accessed on 2 July 2012).
12. Ozcan, K.; Balkaya, N.; Bilgili, E.; Demir, G.; Ucan, N.; Bayat, C. Modeling of methane distribution in a landfill using genetic algorithms. *Environ. Eng. Sci.* **2009**, *26*, 441–449.
13. Molins, S.; Maayer, K.U.; Scheutz, C.; Kjeldsen, P. Transport and reaction process affecting the attenuation of landfill gas in cover soils. *J. Environ. Qual.* **2008**, *37*, 459–468.

14. Yu, L.; Batlle, F.; Carrera, J.; Lloret, A. Gas flow to a vertical gas extraction well in deformable MSW landfills. *J. Hazard. Mater.* **2009**, *168*, 1404–1416.
15. Renou, S.; Givaudan, J.G.; Poulain, S.; Dirassouyan, F.; Moulin, P. Landfill leachate treatment: Review and opportunity. *J. Hazard. Mater.* **2008**, *150*, 468–493.
16. Decreto Legislativo 13 gennaio 2003, n. 36. Attuazione della direttiva 1999/31/CE relativa alle discariche di rifiuti. (GU n. 59 del 12.03.2003—Suppl. Ordinario n. 40). Available online: http://www.camera.it/parlam/leggi/deleghe/03036dl.htm (accessed on 26 September 2012).
17. Decreto Legislativo 3 aprile 2006, n. 152. Norme in materia ambientale. (GU n. 88 del 14.04.2006—Suppl. Ordinario n. 96). Available online: http://www.camera.it/parlam/leggi/deleghe/06152dl.htm (accessed on 26 September 2012).
18. Panno, D.; Messineo, A.; Dispenza, A. Cogeneration plant in a pasta factory, energy saving and environmental benefit. *Energy* **2007**, *32*, 746–754.
19. Messineo, A.; Volpe, R.; Marvuglia, A. Ligno-cellulosic biomass exploitation for power generation: A case study in Sicily. *Energy* **2012**, *45*, 613–625.
20. Messineo, A.; Volpe, R.; Asdrubali, F. Evaluation of net energy obtainable from combustion of stabilised olive mill by-products. *Energies* **2012**, *5*, 1384–1397.
21. Wiszniowski, J.; Robert, D.; Surmacz-Gorska, J.; Miksch, K.; Weber, J.V. Landfill leachate treatment methods: A review. *Environ. Chem. Lett.* **2006**, *4*, 51–61.
22. De Marchis, M.; Napoli, E.; Armenio, V. Turbulence structures over irregular rough surfaces. *J. Turbul.* **2010**, *11*, 1–32.
23. Jenkins, B.M.; Mannapperuma, J.D.; Bakker, R.R. Biomass leachate treatment by reverse osmosis. *Fuel Process. Technol.* **2003**, *81*, 223–246.
24. Regulatory Authority for Electricity and Gas (AEEG). Available online: http://www.autorita.energia.it (accessed on 10 July 2012).