

Research Article

Energy Recovery from Municipal Solid Waste in Oujda city (Morocco)**Mohammed Saghir^{1,*}, Youssef Naimi¹, Laila Laasri², Mohamed Tahiri³**¹Laboratory of Physical Chemistry of Materials, Faculty of Sciences Ben M'Sik, University of Hassan II Casablanca, B.P. 7955, Casablanca, Morocco²Laboratory of Chemistry Physics Catalysis and Environment, Faculty of Sciences Ben M'Sik, University of Hassan II Casablanca, B.P. 7955, Casablanca, Morocco³Laboratory Interfaces, Materials and Environment, Faculty of Science Ain Chock, University of Hassan II Casablanca, B. P 5366, Casablanca, Morocco

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Abstract

The generation of Municipal Solid Waste (MSW) is inevitable. With population growth year after year and the increase in the standard of living, the quantities of waste are increasing exponentially and their efficient management has become a priority to municipal authorities worldwide. The Moroccan government has recognized the importance of effective sustainable resource management and the implementation of a national strategy as waste management. In Morocco, the Secretariat of State for Sustainable Development and the Ministry of the Interior have developed a waste management strategy called the National Household Waste Management Program (PNDM), which was implemented with the support of the World Bank, which targets for the next few years the quantitative objectives of waste collection (90% in 2020), the implementation of controlled landfills and the development of waste sorting, recycling and valorization. Waste energy recovery is the most optimal management solution that not only eliminates the large quantities of waste produced each day but also creates the energy needed for a constantly growing population. The objective of this research work is to assess the municipal solid waste potential for electrical and thermal energy generation and biogas production using three modes of energy recovery (combustion, gasification and anaerobic digestion) in Oujda city (Morocco). The maximum electric load generated is 177.39 GWh from waste gasification with electrical efficiencies of 17.3%. Whereas for thermal energy, a maximum value of 277.17 GWh is generated by direct combustion of MSW. For anaerobic digestion, the maximum potential methane generation capacity is 2.44 10⁶ m³/year in 2014.

Keywords: Municipal Solid Waste; Energy recovery; Combustion; Gasification; Anaerobic digestion; Oujda city**1. Introduction**

Every day, the human activity produces more than 10 billion kilos of municipal solid waste or approximately between 120 tonnes of waste per second. M. Elsen and al. estimates an increase of 40% in 2020 of the quantity of waste in the world [1]. Thus the management and recovery of waste are necessary for every country.

The quantity of municipal solid waste (MSW) generated, actually, in Morocco, totaled 6.98 million tonnes a year, 5.51 million tonnes in urban zones mean of 0.76 kg/inhabitant/day and 1.47 million tonnes in rural areas with a mean of 0.3 kg/inhabitant/day. These quantities will continue to increase from 6.98 million tonnes in 2018 to about 9.3 million tonnes a year in 2030[2].

To deal with this situation, the Moroccan government, in 2006, provides a first law 28-00 on solid waste management and opted for a gradual transformation by launching, in 2007, a 15- years program (National Municipal Solid Waste Management Program (PNDM)) with support from the World Bank. This approach has substantially improved the municipal solid waste management system which has become more efficient than ever before. Thus it has been

registered a waste collection rate of more than 85% in the majority of operational areas by company agents, this rate will reach 90% by 2020 according to the objectives of the PNDM. Energy recovery from MSW appears as an interesting solution to solve the problem of multiplication of waste, but also it responds to energy and climate challenges that countries are facing around the world.

The Moroccan strategy for the promotion of renewable energy sets up an objective of increasing the part of the renewable energy at 42 % of the electric balance sheet in 2020. This objective can easily be achieved by introducing the recovered energy from municipal solid waste, not only to align with the national strategy but also to reduce the effects of global warming.

The objective of this research work is to assess the municipal solid waste potential for electrical and thermal energy generation and biogas production using three recovery processes (combustion, gasification and anaerobic digestion) in Oujda city (Morocco).

2. Strategy of municipal solid waste management in Morocco

Municipal solid waste management in Morocco focused on "clean-up" only and paid little attention and resources to waste disposal. This situation had significant negative economic, environmental and social consequences. In fact,

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the cost of environmental degradation was equivalent to 0.5% of GDP in 2000 and decreased in 2014 to 0.26% according to the World Bank Group Report of January 2017 [3]. This improvement is due to the new strategy adopted by the Moroccan government for the management of municipal solid waste since 2006 by the promulgation of the first law 28-00 on the management and disposal of waste reforming the waste sector.

In 2008, the government launched a three-phase, 15-year National Municipal Solid Waste Program (PNDM) with the support of the World Bank. These phases are:

Phase 1: 2008–2012, start-up; phase 2: 2013–2017, increased capacity; phase 3: 2018–2030, roll-out throughout the country. Its goals were set out as follows:

- To ensure the collection and the cleaning of municipal solid waste to reach a rate of collection of 90% in 2020.
 - Rehabilitate all old landfills 100% by 2020.
 - To develop the sector of “tri-recycling-valorization”, with pilot actions of sorting, to reach a rate of 20% of recycling in 2020.
 - To train and sensitize all the actors concerned with the problems of waste.
- Currently, the majority of the great urban areas have new controlled landfills and others are in the course of construction. The overall cost of PNDM is estimated at close to 40 billion DH, distributed as follows [4]:
- Collection and cleaning: 72 %.
 - Construction and exploitation of controlled landfills: 14.6%.
 - Rehabilitation and closure of wild dumps: 6.3%.
 - Sorting, recycling and recovery: 1.8%.
 - Communication, raising awareness and training: 1.8 %.

The collection of municipal solid waste is the responsibility of urban municipalities. However, some large cities have delegated waste management to private companies.

The average composition of Moroccan municipal solid waste is represented in figure 1.

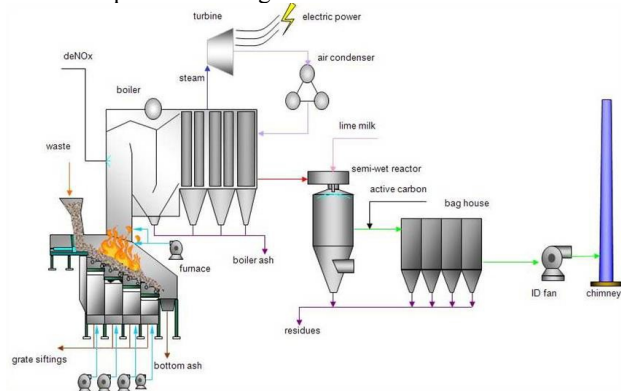


Fig.1. Composition of municipal solid wastes in Morocco [5]

3. Production of energy by municipal solid waste

Various types of technologies are studied to produce energy from waste: Direct combustion, gasification, production and

valorization of biogas.

3.1. Direct combustion of waste for energy production

Direct combustion is used as the main process to treat municipal solid waste and also provides electricity as a supplementary function [6]. Direct combustion of municipal solid waste in specific furnaces produces heat, which is used for heating and electricity generation. A direct combustion municipal solid waste system (Figure 2) consists of a combustion furnace, a boiler to produce heat, and a flue gas treatment system to eliminate the harmful effects of toxic gases. The steam generated by the combustion system boiler is used for heating, domestic hot water or to produce electricity from turbines.

The calorific value of municipal solid waste depends on the content of organic matter and moisture in the waste. On average, municipal solid waste has a heating value of around 13000kJ/kg [8]. Direct waste combustion plants for energy production have an electrical efficiency of 15.3% and a thermal efficiency of 42.5% [9].

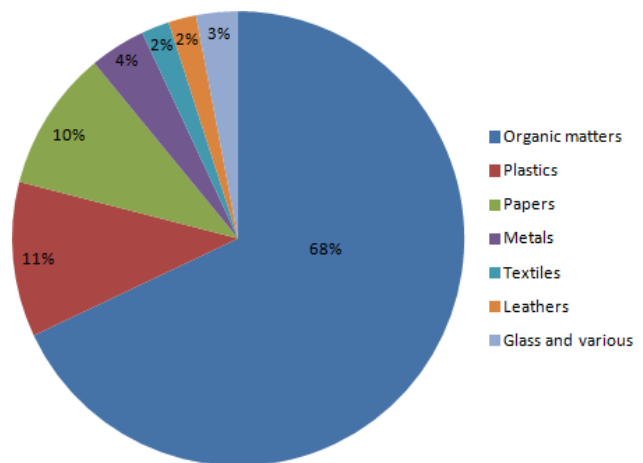


Fig. 2. Direct combustion of waste for energy production [7]

3.2. Energy production by gasification of municipal solid waste

Waste gasification is a thermal process that occurs at temperatures generally between 900 and 1200°C in the presence of a small amount of oxygen, this process requires an external thermal energy source for gasification reactions (endothermic reaction) [10]. Thermochemical gasification reactions occur in oxygen deficiency (between 30 and 50% of stoichiometric demand) in order to avoid total combustion of the solid in order to produce syngas [11]. The gas produced by gasification is called synthesis gas, at a low calorific value than about 4 to 6MJ/m³ [12] can be burned directly or used as fuel for internal combustion engines. The gas produced (synthesis gas) can be used in the manufacture of chemicals [12], and can also be converted into liquid hydrocarbons of various forms. The advantage of gasification is a higher electrical efficiency compared to combustion. In a combined cycle gas thermal power plant, the electrical efficiency is increased and the steam temperature decreases. The thermal energy produced by gasification is lower than that produced by direct combustion. The gasification process is used for electricity production [13, 14]. Gasification plants (figure 3) have a net electrical efficiency of 27.2% and a net thermal efficiency of 24.5% [9].

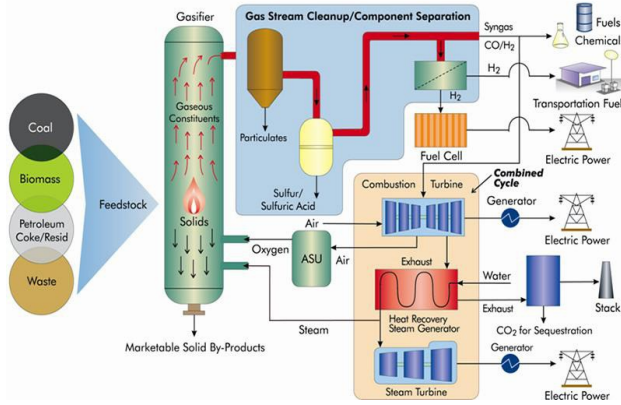


Fig.3. Gasification system (Gasifier) [15]

The gas produced by the gasification process (synthesis gas) contains various compounds: halogens, alkaline compounds, tars and heavy metals. Before using synthesis gas in electrical systems, these compounds must be removed.

3.3. Quantification of energy by direct combustion and gasification of municipal solid waste

There are several empirical equations for calculating the heating values of a substance. There are two methods for determining the heating values: the open calorimeter and oxygen bomb calorimeter. Researchers have developed a mathematical model to calculate the low heating value of municipal solid waste. This model (Eq.1) is expressed as follows [16]:

$$LHV = 23(F + 3.6PA) + 160PL \quad (1)$$

In which (LHV) is the low heating value of municipal solid waste (Btu/lb), (PL) is percentage by weight of plastic in MSW, (F) is percentage by weight of food in MSW and (PA) is percentage by weight of paper in MSW.

To quantify energy production, the Waste-To-Energy plant generates steam to a standard power plant with a temperature of 120°C and a pressure of 135kPa to produce electrical and thermal energy. The heating values of municipal solid waste compounds are (table 1):

Table 1. Heating values of municipal solid waste compounds [17]

Municipal solid waste compounds	Heating value (kJ/kg)
Iron	420
Metal	544
Glass	628
Water	2636
Combustibles (paper, plastics, textiles, wood)	18400

Another more sophisticated model and it are experimentally validated by the researchers (Eq.1) allows calculating the heating value of MSW:

$$HV_{MSW} = HV_{comb}X_{comb} - HV_{H_2O}X_{H_2O} - HV_{glass}X_{glass} - HV_{metal}X_{metal} \quad (2)$$

Where:

- $HV_{MSW}(kJ/kg)$: The heating value of municipal solid waste;

- $HV_{comb}(kJ/kg)$: The heating value of combustibles;
- $HV_{H_2O}(kJ/kg)$: Heat loss of water in MSW;
- $HV_{glass}(kJ/kg)$: Heat loss of glass in MSW;
- $HV_{metal}(kJ/kg)$: Heat loss of metal in MSW;
- X_{comb} : The fraction of combustible matter in MSW;
- X_{H_2O} : The fraction of water in MS;
- X_{glass} : The fraction of glass in MSW;
- X_{metal} : The fraction of metal in MSW;

So by substituting the numerical values for the calorific value of the waste compounds in model 2, we find (Eq.3):

$$HV_{MSW} = 18400X_{comb} - 2636X_{H_2O} - 628X_{glass} - 544X_{metal} \quad (3)$$

Where

HV_{MSW} in (kJ/kg)

Wet materials must be removed to improve combustion efficiency and maximize energy production per tonne of MSW. The steam cycle option is the most suitable for gasification, and it does not require pre-treatment of the gas, as the boiler burns all combustible products [18]. The electrical efficiency of a gasification plant is about 27. 2% and that of the combustion plant is about 15.3% [9].

The steam cycle is the simplest option for energy recovery. It does not need gas pre-treatment, because tar is burned in the combustor and cannot damage the boiler [18]. The electrical efficiency of gasification–steam cycle plant is about 27.2 %, and electrical efficiency of the combustion–steam plant which is about 15.3% [9].

Then, the production of electrical energy and thermal energy by gasification–steam cycle plant or combustion–steam plant is calculated by the following equation (Eq. 4) [19]:

$$E(kJ) = M * HV_{MSW} * \gamma \quad (4)$$

Where:

- $E(kJ)$: Production of electrical energy and thermal energy;
- $M(kg)$: Quantity of municipal solid waste;
- $HV_{MSW}(kJ/kg)$: The heating value of municipal solid waste;
- γ : Efficiency of gasification plant or combustion plant;

3.4. Energy production by anaerobic digestion of municipal solid waste

Anaerobic digestion, or methanisation, is the natural process of degrading organic matter in the absence of oxygen. The main advantage of anaerobic digestion is that almost all of the degraded organic matter is in the form of biogas. Different micro-organisms transform complex organic substrates into simple molecules (monomers: acids, alcohols), then into biogas, contains from 45% to 70% methane [20], that can be recovered in the form of energy. The anaerobic digestion process takes place in several stages, with bacteria adapted to each stage, just like food digestion: (1) Hydrolysis and acidogenesis; (2) Acetogenesis; (3) Methanogenesis [21].

The degradation of organic waste in landfills produces biogas, which is composed mainly of methane and carbon dioxide [22]. Methane is the main gas for global warming.

The extraction and use of methane from landfills not only benefits the environment by mitigating climate change, but also for the production of heat and electricity [23]. Biogas can be used to produce heat, electricity or both (cogeneration). In addition, it can also be injected into natural gas networks or used as a biofuel [24]. The energy content of biogas depends mainly on its methane content, so the biogas becomes combustible when it contains 25% of the methane. The energy value of biogas at 60% of CH₄ is 2.16*10⁴kJ/m³ [25].

Landfill gas can be used directly in gas boilers and most internal combustion engines, while gas turbines and microturbines will require a treatment step by biological purifiers to remove siloxane and hydrogen sulfide [26].

The Biogas-to-CHP (combined heat and power) plant is the most widely used system in the world. The electricity generated by the Biogas-to-CHP system is fed into the electricity grid. The electrical and thermal efficiencies of different Biogas- to-CHP systems are presented in Table 2 [27].

Table 2. Efficiency and electricity input for CHP generation from biogas [27, 28, 29 and 30]

	CHP electrical efficiency	CHP thermal efficiency
Small-scale biogas plant (%)	33	50
Large-scale biogas plant (%)	40	48

Biogas can be transformed into biomethane after a purification step to leave 97% methane (CH₄) in the gas. Biomethane can be used as a fuel or injected into the natural gas grid [31].

Several types of mathematical models exist to calculate the production of biogas. They are generally based on decomposition kinetics of zero, of first order and second order. Others are of digital nature and have much precision, but their use requires several inputs that are not always at the disposal of managers [32].

First-order models are the most widely used in the world because of the compromise between accuracy and ease of use [33]. Among the first-order models, we distinguish the LandGEM model (Landfill Gas Emissions Model) [32].

The Land-GEM model is an estimation model that estimates the production rates of methane, carbon dioxide, non-methane organic compounds (NMOCs) and air pollutants from municipal landfills. The model is represented by the equation (Eq.5) [34]:

$$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 k L_0 \left(\frac{M_i}{10}\right) e^{-kt_{i,j}} \quad (5)$$

Where:

- Q_{CH_4} (m³.year⁻¹): Annual methane generation in the year of the calculation;
- i : One-year time increments;
- n : Number of years calculated (year of the calculation - initial year of waste acceptance);
- j : 0.1 year time increment (cutting the year into tenth);
- k (year⁻¹): Methane generation rate;
- L_0 (m³.Mg⁻¹): Potential methane generation capacity;
- M_i (Mg): Mass of waste accepted in the ith year;

- $t_{i,j}$: Age of the jth section of waste mass
- M_i accepted in the ith year;

LandGEM offers the value of constant k and the potential value of methane production L_0 , both CAA (Clean Air Act) and the other for AP₄₂ standards. It is recommended to use standard AP₄₂ standard values for landfills.

The default methane content in the landfill gas is 50%, which are both the industry standard value and the default value recommended by LMOP (Landfill Methane Outreach Program) [35].

4. Assessment of the energy recovery potential from municipal solid waste in Oujda city

4.1. Description of the study area – Oujda city

The city of Oujda is located in the northeast of Morocco, in the Oriental Region, the third largest region of the Kingdom. The city of Oujda enjoys a Mediterranean climate with a mild to cold and rainy winter and a warm summer. The city of Oujda has a population of 494 252, according to the latest general population census in 2014 [36]. The economy of Oujda is mainly oriented towards agriculture, mining, trade and crafts, but also presents interesting energy assets. Population growth has a direct influence on the waste sector, but an average of 143 454 tonnes [37] of waste is collected every year in Oujda within 2011 to 2014.

4.2. Evolution of the quantity of municipal solid waste in Oujda

The controlled landfill of Oujda is located south of the city about 10 km, in a non-agricultural zone with a very clayey (impermeable) soil and an area of 130 ha, this landfill entered the operating phase in 2005 [37], benefiting from several modern treatment technologies (selective sorting, recycling, waste treatment, leachate management and treatment, energy conversion station, biogas pumping station).

The landfill is fenced and has a weight scale, an operating building, a meteorological station, a clogging of the base and also a drainage system for leachate treatment and biogas capture. In particular, vertical wells for biogas collection were set up, allowing the collection of biogas to achieve energy recovery from a biogas cogeneration plant, totaling an installed electrical power of the order of 6.9 MW_{el}. The electricity generated is then injected into the distribution network, for a total of 19.000 MW_{el} per year [38].

Table 3. Tonnage (in tonnes) of municipal solid waste in Oujda 2011-2014 [38, 5]

Years	2011	2012	2013	2014
Tonnage (t)	134 828	139 801	146 313	152 873
Fermentable waste	73,25%			
Moisture	65%			

Table 3 shows the annual amount of waste collected from 2011 to 2014 in the city of Oujda, as well as the percentage of fermentable waste in MSW.

4.3. Direct combustion of municipal solid waste for

energy production in Oujda

The electricity and thermal energy production from municipal solid waste can be calculated knowing the calorific power and the organic composition. A calculation is made to evaluate the amount of energy recovery for MSW if the waste is incinerated.

Table 4 shows the results of the evaluation of the electricity and thermal energy production by direct combustion for the city of Oujda. We observe the growth of energy (electricity and thermal energy) over the years, as well as electricity production in 2014 is 99.78 GWh/year and thermal energy reaches 277.17 GWh/year.

For the direct combustion plant, the production of thermal energy is higher than that of electrical energy.

Table 4. Production of electricity and thermal energy by direct combustion of municipal solid waste in Oujda

	2011	2012	2013	2014
Electricity (GWh)	88.00	91.25	95.50	99.78
Thermal energy (GWh)	244.46	253.47	265.28	277.17

4.4. Gasification of municipal solid waste for energy production in Oujda

According to the composition of household waste in Morocco and energy efficiencies of gasification, as well as equations 3 and 4, a calculation is made to evaluate the amount of energy recovery for MSW if the waste is gasified.

The obtained results (Table 5) shows that the production of electricity and thermal energy increase gradually over the years with a relatively higher electricity production than thermal energy unlike the results found using MSW combustion plant.

4.5. Energy production through anaerobic digestion of municipal solid waste in Oujda

The application of the LandGEM Model (equation 5) allowed estimating the quantities of biogas produced by the landfill (table 6).

Table 5. Production of electricity and thermal energy by gasification of municipal solid waste in Oujda

	2011	2012	2013	2014
Electricity (GWh)	156.45	162.22	169.78	177.39
Thermal energy (GWh)	140.92	146.12	152.93	159.78

The parameter, k , determines the rate of methane generation for the waste mass in the landfill. The higher the k value, the faster the methane production rate increases over time [34]. In the case of the Oujda controlled landfill $k = 0.05 \text{ year}^{-1}$ used.

The potential methane production capacity L_0 depends solely on the type and composition of the waste placed in the landfill. The higher the cellulose contents of the waste, the higher the value of L_0 [34]. In the case of Oujda controlled landfill $L_0 = 170 \text{ m}^3/\text{Mg}$ is used.

The lower calorific value of methane is 35.8 MJ/m^3 [39] and according to table 2, the production of electricity and thermal energy by a small biogas plant for fermentable waste in Oujda:

Table 6. Values of tonnage of fermentable waste stored (ton), biogas production (m^3), and methane production (m^3) for each year from 2011 to 2014 in Oujda

	2011	2012	2013	2014
Fermentable waste stored (ton)	98761.51	102404.23	107174.27	111979.47
Biogas production (m^3)	0	$1.64 \cdot 10^6$	$3.26 \cdot 10^6$	$4.88 \cdot 10^6$
Methane production (m^3/year)	0	$8.21 \cdot 10^5$	$1.63 \cdot 10^6$	$2.44 \cdot 10^6$

Table 7. Production of electricity and thermal energy by a small biogas plant system in Oujda

	2011	2012	2013	2014
CHP electrical energy (GWh)	0	2.70	5.30	8.00
CHP thermal energy (GWh)	0	4.10	8.10	12.15

The results shown in table 7, shows the evolution of the production of electrical energy and thermal energy by a biogas-to-CHP plant of fermentable waste in Oujda. Energy production is increasing over the years. The electricity production in 2014 is 8 GWh and thermal energy is 12.15 GWh. So for small-scale biogas plants, thermal energy production is higher than electricity production.

5. Conclusions and recommendations

According to the obtained results based on the calculations of the electricity and thermal energy produced by combustion, gasification and aerobic digestion of MSW of Oujda city, we can conclude that the energy recovery of MSW can make a significant contribution to the national energy balance. Combustion, as modeled here, would have the highest gate fee and the greatest capital cost. A market for the thermal product is extremely important in terms of gate fee and greenhouse gas production. In theory, gasification is a more suitable technology for Morocco where the market for the thermal product is difficult; however, the constraint with gasification of MSW is the technology which is not yet proven at commercial scale.

Biogas technology requires significantly fewer investment costs than the thermal conversion technologies (incineration and gasification) and have smaller gate fees. It should be noted that biogas production is not an alternative to incineration or gasification because biogas is produced from the organic fraction of MSW and thermal treatment is applied to the non-organic, non-recyclable fraction.

Converting municipal solid waste (MSW) into energy has the environmental benefit of reducing greenhouse gases to stop global warming, preventing contamination of water and air, and reducing dependence on oil and other fossil fuels for energy production.

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