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Research Article

ENERGY RECOVERY FROM WASTE IN FEZ CITY (MOROCCO)

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ABSTRACT

Morocco's commitment to the development of renewable energy was confirmed at COP 22 (Conference of Parties) in Marrakech, during which Morocco announced the decision to increase the share of renewable energies from 42% of installed capacity planned for 2020 to 52% by 2030.
Morocco's energy strategy, which attaches great importance to the development of renewable energies and energy efficiency, is based on four fundamental objectives, aimed at:

- Enhancing security of supply and energy availability;
- Generalized access to energy at competitive prices;
- Demand management;
- The preservation of the environment.

Among these renewable energies is biomass.
Household waste in Morocco contains almost 65% to 75% organic matter, so a very large amount of biomass.
Waste recovery is the most optimal waste management solution. It not only eliminates the large quantities of waste produced every day, but also generates the energy needed by a constantly changing population.The objective of this research work is to assess the household waste potential for electrical and thermal energy generation in Fez city (Morocco) using two modes of energy recovery: combustion and anaerobic digestion.
The maximum electric generated was 228.04 GWh/year from direct combustion of household waste, whereas for thermal energy, a maximum value of 633.46 GWh/year in 2016. For anaerobic digestion, the maximum electric generated was 50.02 GWh/year and thermal energy generated was 75.79 GWh/year in 2016.
Keywords: Household waste, energy recovery, combustion, anaerobic digestion, Fez city.

1. INTRODUCTION

Every day, the human activity produces more than 10 billion kilos of waste or approximately between 120 tons of waste per second, so the forecasts estimates an increase of 40% in 2020 of the quantity of waste in the world [1], thus, the management and the recovery of waste was drastically primordial all over the world including Morocco.

The quantity of household waste generated, actually, in Morocco, totalled 6.98 million tons a year, with 5.51 million tons in urban zones with a mean of 0.76 kg/inhabitant/day and 1.47

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million tons in rural areas with a mean of 0.3 kg/inhabitant/day. These quantities will continue to increase from 6.98 million tons in 2018 to about 9.3 million tons a year in 2030 [2].

To deal with this situation, the Moroccan government enacted, in 2006, a first law 28-00 on solid waste management and opted for a gradual transformation by launching, in 2007, a 15-year, Three-phase national household waste management program (PNDM) with support from the World Bank. This approach has substantially improved the household waste management system which has become more efficient than ever before. Thus, it has been registered a 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 [3].

Energy recovery from household waste appears as an interesting solution not only to solve the problem of multiplication of waste but also it responds to energy and climate challenges that are facing countries around the world.

The Moroccan strategy for the promotion of the renewable energy sets up an objective of increasing the part of the renewable energy at 52% of the electric balance sheet in 2030. This objective can easily be achieved by introducing the recovered energy from household waste, not only to align with the national strategy but also to reduce the effects of global warming [4].

The objective of this research work is to estimate the energy potential of household waste in the controlled landfill of Fez (Morocco), using two energy recovery processes: direct combustion and anaerobic digestion. This article also includes a comparative study between the theoretical and experimental energy potential of biogas of the landfill Fez landfill..

2. METHODS

A. Controlled landfill of Fez city

The controlled landfill of Fes is of type classifies I, which makes it possible to collect only the household waste. However, it is equipped by specific installations to receive waste of class II (tannery sewage sludge and scrap).

The landfill receives 100 trucks, on average, by day, which generates a quantity of waste equivalent to 700 tons. Most of wastes are the household wastes, transported by the trucks of collecting of the domestic buckets of refuse (BOM), and of comparable waste coming from the points from transfer of waste. The remaining part distributed between ordinary waste (Green wastes, Waste of demolitions, the ground) and of special waste (Sludge from the wastewater treatment plant and tannery waste).

Table 1. Various types of waste codified in the controlled landfill of Fez

Types of waste	Code
Household wastes	DM
Green wastes	DV
Tannery scrap	DT
Mixed waste assimilated	DMA
Mixed wastes	DM
Industrial waste	DI
Waste of demolition	DD
Waste of sweeping	DB

The weighing of the waste takes place via a weighing bridge or also called the electronic flip-flop provided with six sensors underneath connected to an apparatus called the terminal, which allows the display of the mass on the weighbridge bridge, its capacity is 60 tons and its uncertainty is 20 kg per tons, this uncertainty considered negligible.

The terminal linked to a computer, which records the waste mass by the user and by software called Transistor, on the screen of the computer there are boxes, each box comprises information. The user indicates the number of the truck coming installed on the weighbridge, the type of waste collected (household waste or similar household waste); the name of the carrier and the place of loading, and the computer displays other information concerning the masses.

Indeed, as soon as the truck installed on the weighbridge atthe entrance, the gross mass or also called the input mass:

$$M_{entry} = M_{truck} + M_{carrier} + M_{waste} \tag{1}$$

Where:

- M_{entry}: Mass of entry;
- M_{truck}: Mass of the truck;
- $M_{carrier}$: Mass of the carrier;
- M_{waste}: Mass of waste.

The mass of entry displayed on the terminal then on the screen of the computer.

After the truck landfills, is installed on the weighbridge and there is displayed the mass of exit on the screen of the computer:

$$M_{exit} = M_{truck} + M_{carrier} \tag{2}$$

Where:

- M_{exit}: Mass of exit.

Therefore, we can deduce that the mass of waste is equal to the difference between the two masses:

$$M_{waste} = M_{entry} - M_{exit} \tag{3}$$

This calculation is carried out by the computer and gives the result directly, and then the user records this result to add the whole with the results of each day. This operation makes it possible to have the mass of the waste buried each day.

B. Waste-to-energy technologies

1)Direct combustion of waste for energy production

Direct combustion is used as the main process to treat household waste and also provides electricity as a supplementary function [5]. Direct combustion of household wastes in specific furnaces produces heat, which is used for heating and electricity generation. A direct combustion plant household waste (Figure 1) 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.

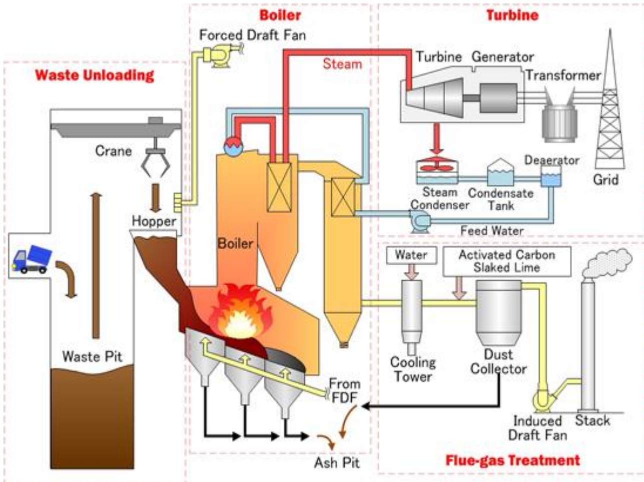

Figure 1. Direct combustion of waste for energy production [6]

The calorific value of household waste depends on the content of organic matter and moisture in the waste. On average, household waste has a heating value of around 13000kJ/kg [7]. Direct waste combustion plants for energy production have an electrical efficiency of 15.3% and a thermal efficiency of 42.5% [8].

2) Calculation of energy produced by direct combustion of household waste

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 [9]. The heating values of household waste compounds are (table 2):

Table 2. Heating values of household waste compounds [10]

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

Sophisticated model and it are experimentally validated by the researchers (Eq.4) allows calculating the heating value of household waste:

$$HV_{HW} = HV_{comb}.X_{comb} - HV_{water}.X_{water} - HV_{glass}.X_{glass} - HV_{metal}.X_{metal} \quad (4)$$

Where:

- HV_{HW} (kJ/kg): Heating value of household waste;
- HV_{comb} (kJ/kg): Heating value of combustibles;
- HV_{water} (kJ/kg): Heat loss of water in household waste;
- HV_{glass}(kJ/kg): Heat loss of glass in household waste;
- HV_{metal}(kJ/kg): Heat loss of metal in household waste;
- X_{comb}: Fraction of combustible matter in household waste;

- X_{water} : Fraction of water in household waste;
- X_{glass}: Fraction of glass in household waste;
- X_{metal}: Fraction of metal in household waste;

So by substituting the numerical values (table 2) for the calorific value of the waste compounds in equation 4, we find (Eq.5):

$$HV_{HW} = 18400.X_{comb} - 2636.X_{water} - 628.X_{glass} - 544.X_{metal} \quad (5)$$

Then, the production of electrical energy and thermal energy by combustion–steam plant are calculated by the following equation (Eq. 6) [11]:

$$E = M * HV_{HW} * \gamma \quad (6)$$

Where:

- E(kJ): Production of electrical energy and thermal energy;
- M(kg): Quantity of household waste;
- HV_{HW} (kJ/kg): Heating value of household waste;
- γ: Efficiency of combustion plant;

3)Energy production by anaerobic digestion of fermentable waste

Household waste in Morocco contains 68% organic matte [12]. The landfilling of organic waste generates the production of a gas rich in methane (45 to 70% CH_4 [13]) by anaerobic biodegradation of organic waste. This gas is then called biogas. It is mandatory to harvest this biogas because the action of methane on the greenhouse effect is 20 times greater than that of CO_2.

The anaerobic digestion process takes place in several stages, with bacteria adapted to each stage:

- Hydrolysis and acidogens: the first stage known as hydrolysis and acidogens is provided by hydrolytic bacteria. These bacteria transform complex organic matter (lipids, cellulose, starch and proteins) into simpler compounds, namely volatile fatty acids (acetic acids, propanoic acid and buturic acid) and alcohols (methanol and ethanol);
- Acetogenesis: During this stage, the acidogen products are converted into acetates (CH_3COO^-) and hydrogen (H_2);
- Methanogenesis: this step transforms acetate into methane and carbon dioxide, and carbon dioxide and hydrogen into methane;

Indeed, methane is an excellent fuel ($1Nm^3$ of CH_4 = 9.67 kWh [14]). Biogas can therefore be used as fuel, with some conditioning, for various energy production solutions such as boilers, engines and turbines.

The production of biogas by the controlled landfill results in a significant increase in indoor pressure compared to atmospheric pressure. The permeability of the waste being 10 times greater in the horizontal direction than in the vertical direction (because of compaction) [15], then the biogas migrates preferentially towards the side walls of the landfill.

There are two main biogas collection systems in controlled landfills:

- Vertical well biogas collection systems: These systems are not 100% effective because the vertical permeability of the waste is often low;
- Horizontal well biogas collection systems: These systems are placed at different heights in the controlled landfill. They must be strong enough to withstand compactors and bulldozers, so they are usually surrounded by a layer of gravel. This type of collection is generally reserved for shallow controlled landfills.

The optimal solution is often a combination of the two: horizontal wells to capture biogas near the landfill walls and vertical wells to capture it inside the waste massif.

Cell capping consists of installing a final cover made of compact materials taken from the mining site (clay), then a permeable layer (geomembrane), a natural filter (sand) and artificial protective filters (geotextile). The surface of the landfill cell will be covered to prevent the emission or migration of biogas and to limit water infiltration that produces leachate.

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 sulphide [16].

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, while the heat is used for heating. The electrical and thermal efficiencies of different Biogas-to-CHP systems are presented in Table 3 [17].

Table 3. Electrical and thermal efficiency for Biogas-to-CHP systems [17, 18, 19 and 20]

	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 (CH_4) in the gas. Biomethane can be used as a fuel or injected into the natural gas grid [21].

Organic waste is degraded by complex biological and chemical processes. At the beginning of landfilling, the waste follows aerobic degradation, and after the amount of waste increases layer by layer, it follows anaerobic degradation. All models used for biogas prediction in the world are based on the first-order decay model [22]. Among the first-order models, we distinguish the LandGEM model (Landfill Gas Emissions Model) [23].

First-order models are the most widely used in the world because of the compromise between accuracy and ease of use [24]. Among the first-order models, we distinguish the LandGEM model (Landfill Gas Emissions Model) [23].

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, in its double summation form, is represented by the equation (Eq.7) [25]:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k.L_0.(\frac{M_i}{10}).e^{-k.t_{i,j}} \tag{7}$$

Where:

- $Q_{CH_4}\,(m^3/year)$: 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;
- $L_0\,(m^3.Mg^{-1})$: Potential methane generation capacity;
- $M_i\,(Mg)$: Mass of waste accepted in the i^{th} year;
- $t_{i,j}$: Age of the j^{th} section of waste mass M_i accepted in the i^{th} year;

LandGEM offers the value of constant k and the potential value of methane production L_o, 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) [26].

3. RESULTS

A. Tonnages of household waste in Fez

The table below shows the tonnages of household waste received by the controlled landfill of Fez, as from the year of opening of the landfill in 2004 until 2016:

Table 4. Tonnage of household waste (ton) in the controlled landfill of Fez (2004-2016)

Years	Tonnage (ton)
2004	135 700
2005	153 665
2006	171 550
2007	189 435
2008	207 320
2009	225 205
2010	243 090
2011	260 975
2012	278 860
2013	296 745
2014	314 630
2015	332 515
2016	350 582

From this table (table 4) we see the increase in the tonnage of household waste according to the years, due to population growth in the Fez region.

According to the results of the general population and housing census of 2014, the prefecture of Fez containing 1,150,131 inhabitants, with the rate of increase equal to 1.63% [27].

The average composition and moisture of household waste in Morocco is represented in table 5.

Table 5. Composition of household waste in Morocco [12, 28]

<table>
<tr><th>Type of waste</th><th>Composition / Provenance</th><th>Percentage (%)</th></tr>
<tr><td rowspan="7">Household waste</td><td>Organic matters</td><td>68</td></tr>
<tr><td>Plastics</td><td>11</td></tr>
<tr><td>Papers</td><td>10</td></tr>
<tr><td>Metals</td><td>4</td></tr>
<tr><td>Textiles</td><td>2</td></tr>
<tr><td>Leathers</td><td>2</td></tr>
<tr><td>Glass and various</td><td>3</td></tr>
<tr><td>Moisture</td><td colspan="2">67%</td></tr>
<tr><td>Fermentable waste</td><td colspan="2">73,25%</td></tr>
</table>

B. Direct combustion of household waste for energy production in Fez

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

Table 6 shows the results of the evaluation of the electricity and thermal energy production by direct combustion for the city of Fez. We observe the growth of energy (electricity and thermal energy) over the years, as well as electricity production in 2016 is 228.04 GWh/year (26.03MW_{el}) and thermal energy reaches 633.46 GWh/year (72.31MW_{th}).

Table 6. Production of electricity and thermal energy by combustion of municipal solid waste in Fez

Years	Electricity (GWh/year)	Thermal energy (GWh/year)
2004	88.27	245.19
2005	99.95	277.65
2006	111.59	309.97
2007	123.22	342.28
2008	134.86	374.60
2009	146.49	406.92
2010	158.12	439.23
2011	169.76	471.55
2012	181.39	503.86
2013	193.03	536.18
2014	204.66	568.49
2015	216.29	600.81
2016	228.04	633.46

C. Energy production through anaerobic digestion of household waste in Fez

The application of Land-GEM Model (equation 7) allowed estimating the quantities of methane produced by the landfill (table 7).

The methane production rate, k, determines the methane production rate for the waste mass in the landfill. The higher the k value, the faster the methane production rate increases and decreases rapidly over time [29]. In the case of the Fez controlled landfill $k = 0.05$ $year^{-1}$[28] are used.

The potential methane production capacity L_0 depends solely on the type and composition of the waste placed in the landfill. The highe the cellulose con tents of the waste, the higher the value of L_0 [29]. In the case of Fez controlled landfill L_0=170 m^3/Mg [28] is used. The lower calorific value of methane is 35.8MJ/m^3 [31].

Table 7. Production of electricity and thermal energy by anaerobic digestion of fermentable waste in Fez

Years	**Methane production ($\times 10^5 m^3$)**	**Electricity (GWh/year)**	**Thermal energy (GWh/year)**
2004	8.26	2.71	4.10
2005	17.21	5.64	8.55
2006	26.82	8.80	13.33
2007	37.05	12.15	18.41
2008	47.86	15.70	23.79
2009	59.24	19.43	29.44
2010	71.15	23.34	35.36
2011	83.57	27.41	41.53
2012	96.47	31.64	47.94
2013	109.80	36.01	54.57
2014	123.60	40.54	61.43
2015	137.80	45.20	68.49
2016	152.50	50.02	75.79

Table 7 shows the results of the production of electrical and thermal energy by anaerobic digestion of fermentable waste in Fez city. We observe the growth of energy (electricity and thermal energy) over the years, as well as electricity production in 2016 is 50.02 GWh/year (or 5.71MW_{el}) and thermal energy production is 75.79 GWh/year (or 8.65MW_{th}).

The biogas plant in Fez currently produces 5.5 MW_{el} of experimental electrical power en 2016, used for public lighting in the city of Fez. So, this experimental value is almost equal to the theoretical value in 2016.

4. CONCLUSION

According to the obtained results based on the calculations of the electricity and thermal energy produced by combustion and anaerobic digestion of household waste of Fez city, we can conclude that the energy recovery of household waste can make a significant contribution to the national energy balance. Combustion, as modelled here, would have the highest gate fee and the greatest capital cost. A market for thermal product is extremely important in terms of gate fee and greenhouse gas production.

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

The conversion of household waste into energy makes it possible to: (1) reduce the amount of waste; (2) reduce methane and carbon dioxide emissions into the atmosphere; (3) prevent contamination of water, air and the environment; (4) reduce dependence on fossil fuels.

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