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Environmental and economic vision of plasma treatment of waste in Makkah

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Abstract

An environmental and economic assessment of the development of a plasma-chemical reactor equipped with plasma torches for the environmentally friendly treatment of waste streams by plasma is outlined with a view to the chemical and energetic valorization of the sustainability in the Kingdom of Saudi Arabia (KSA). This is especially applicable in the pilgrimage season in the city of Makkah, which is a major challenge since the amount of waste was estimated at about 750 thousand tons through Arabic Year 1435H (2015), and is growing at a rate of 3%–5% annually. According to statistics, the value of waste in Saudi Arabia ranges between 8 and 9 billion EUR. The Plasma-Treatment Project (PTP) encompasses the direct plasma treatment of all types of waste (from source and landfill), as well as an environmental vision and economic evaluation of the use of the gas produced for fuel and electricity production in KSA, especially in the pilgrimage season in the holy city Makkah. The electrical power required for the plasma-treatment process is estimated at 5000 kW (2000 kW used for the operation of the system and 3000 kW sold), taking into account the fact that: (1) the processing capacity of solid waste is 100 tons per day (2) and the sale of electricity amounts to 23.8 MW at 0.18 EUR per kWh. (3) The profit from the sale of electricity per year is estimated at 3.27 million EUR and the estimated profit of solid-waste treatment amounts to 6 million EUR per year and (4) the gross profit per ton of solid waste totals 8 million EUR per year. The present article introduces the first stage of the PTP, in Makkah in the pilgrimage season, which consists of five stages: (1) study and treatment of waste streams, (2) slaughterhouse waste treatment, (3) treatment of refuse-derived fuel, (4) treatment of car tires and (5) treatment of slag (the fifth stage associated with each stage from the four previous stages).

Keywords: waste streams, plasma treatment, energy recovery, cost and profit, Makkah

(Some figures may appear in colour only in the online journal)

1. Introduction

The appearance of waste on a large scale is associated with human activity. Most of these waste streams can be divided into two categories: the production cycle waste, and industrial products and material waste.

Thermal treatment is one of the common ways to get rid of waste by direct combustion e.g. industrial furnaces and boilers. This applies to both liquid and solid waste with high calorific value and minimum halogen content. However, a significant amount of harmful substances are released into the atmosphere due to the incomplete burning of hazardous products, since the combustion conditions in these furnaces and boilers do not always match the parameters that are necessary for the complete combustion of organic waste, leading to large emissions of harmful substances into the atmosphere. This is due to the fact that the process of neutralization of organic waste by thermal methods is carried out at temperatures sensitive to the formation of other harmful compounds [1]. As a result, exhaust gases may contain dangerous products of incomplete chemical burning.

Persistent organic pollutants (POPs) are one of the most dangerous pollutants of concern and can migrate to ground water. In addition, chloro-organic waste processing is a serious problem, where the combustion of chloro-organics, in addition to nitrogen oxides and carbon monoxide, may lead to the formation of very toxic products in quantities exceeding the maximum permissible concentration, such as polychlorinated benzopyrene, phosgene, dioxinsdibenzofurans, polyaromatic hydrocarbons, furans, oxides of sulfur, soot, nitrogen oxides, and carbon monoxide. Millions of tons of waste containing chlorine organic compounds are dumped into landfills. Due to their poor biodegradability, the influence of sunlight and the possibility of oxidation by air, chlorinated organic compounds form secondary toxic products (phosgene, etc) [2].

A method for the destruction of toxic organic compounds in a plasma-chemical reactor has been developed [3]. High-temperature plasmas can destroy any waste at the atomic level, making it the most versatile and effective technology. Plasma techniques are applied on a large scale to treat various types of waste, such as municipal, industrial, medical, and military radioactive waste [4]. The use of high temperatures up to 1500 °C–5000 °C generated from hot plasma allows the destruction of organic compounds into atoms with a high degree of conversion to gas [5, 6]. In addition, the destruction of complex compounds in the plasma is very efficient and can occur in the absence of oxygen.

There are many reasons to investigate and increase the efficiency of plasma processing in the Kingdom of Saudi Arabia, such as increasingly strict laws for the treatment of waste streams, the desire to attain high quality of the environment at a reasonable cost, sustainable development, the fact that the circumstances with regard to the complete combustion of organic waste in the furnaces do not comply with international standards, and the limitations of conventional techniques, such as thermal combustion.

The present article introduces an alternative process of direct plasma treatment of all types of waste, as well as an environmental vision and economic evaluation of the use of the gas produced for fuel and electricity production in the Kingdom of Saudi Arabia, especially in the pilgrimage season in the holy city Makkah, based on thermal plasma technology [7].

Furthermore, for the energy recovery analysis, the calculation of the cost and profit of the treatment of waste streams using plasma-treatment modeling are presented.

2. Experimental systems

The plasma-treatment system is the conversion process of waste into gases in a plasma-chemical reactor without the production of environmental contaminants. This process consists of the complex conversion of the organic compounds into a mixture of gaseous species containing hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and carbon monoxide (CO) [8]. The main benefit of plasma treatment is the ability to convert all kinds of organic waste, such as biomass, plastic, paper, food, rubber, etc, into a valuable energy by-product called synthesis gas (abbreviated to syngas).

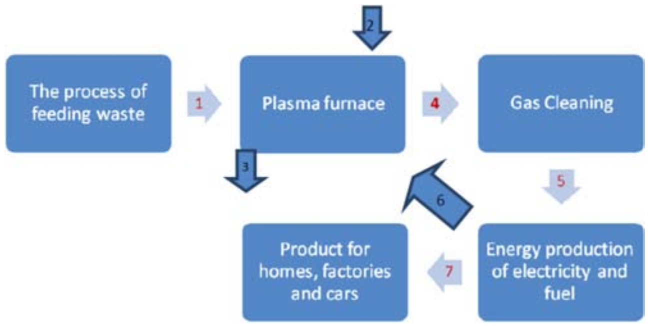

Figure 1. Plasma-treatment process consists of: (1) waste feeding, (2) gas (in air), (3) slag, (4) syngas (containing pollutants), (5) clean syngas, (6) feedback electricity and (7) final product.

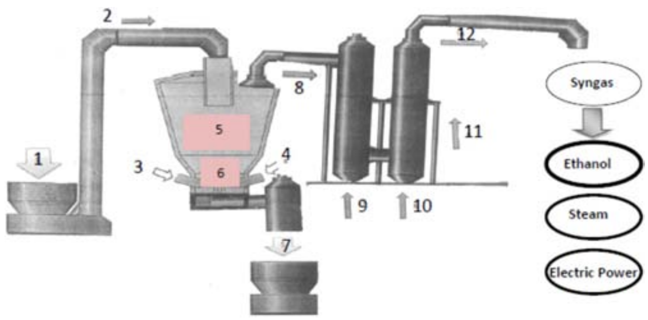

Figure 2. Schematic diagram of a plasma-gasification reactor design with various components: (1) waste feeding, (2) feedstock dropped into the reactor, (3) and (4) plasma torches, (5) low-temperature zone, (6) high-temperature zone, (7) liquid slag, (8) organic part as syngas, (9) syngas cooling system, (10) syngas cleaning system, (11) final product, and (12) cool and clean syngas.

Figure 1 shows a diagram of the plasma-treatment process. The first stage is the input feeding system, which accepts the waste and if necessary pretreats it (for example, by compressing, grinding, chopping, shredding, sorting or crushing it, before sending it to the plasma-treatment reactor). In the second stage, the conversion of the waste to syngas takes place at high temperatures reaching 1500 °C–5000 °C and in the presence of a small amount of oxygen in the plasma-treatment reactor (plasma furnace). The last stage is gas cleaning of the produced syngas and then purification of the gases to get, for example, liquid fuel or to use the gas directly in a gas turbine for electricity generation production as a final product [9].

Figure 2 shows a schematic diagram of a plasma-treatment reactor design with various components. In the material feed part, the feedstock is dropped into the reactor at the top and is forced gravitationally down the reactor to the high-temperature plasma zone where it is decomposed and gasified. The reactor chamber, covered with an insulating refractory material, is able to withstand the high temperatures.

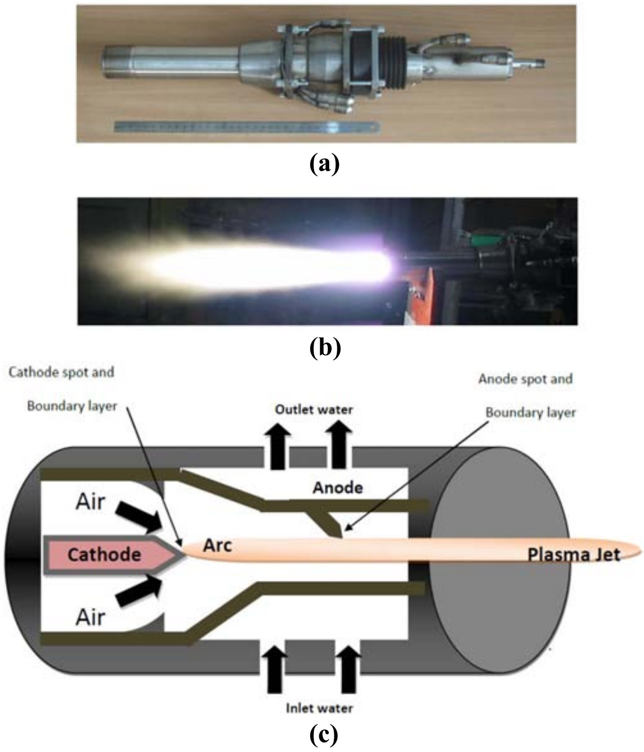

Figure 3. (a) and (b) Examples of plasma torch (non-transferred arc) for the PTP. (c) Schematic diagram of a plasma torch (non-transferred arc).

As shown in figures 3(a) and (b) plasma torches (non-transferred arc) are considered for the Plasma-Treatment Project (PTP) [10, 11]. They are based upon a uniform design principle and encompass a broad range of technical parameters. They may be powered by DC or AC, as well as by combined power systems. Figure 3(c) shows the non-transferred arc torch as a device used for waste treatment. The electric discharges are generated between the cathode and anode, and the electrical energy is transformed into thermal energy. The hot plasma jet emerges from the torch due to the air or gas flow. The air crosses the boundary layer between the gas column and the anode inner surface and is pushed downstream by the pressure of the air flow. The cathode and anode are large enough to be able to withstand the gradual erosion and are water-cooled to deal with the high excursion of temperatures [12–15].

In figure 3, the non-transferred arc torch parameters are: (1) max. output, 100 KW, (2) max. applied voltage, 500 V, (3) max. current 250 A, (4) temperature range of plasma jet, 3000 °C–5500 °C, and (5) max. consumption of working gas, 25 g per day [16, 17].

The performance of plasma-chemical reactors depends on the power of the torch, the type of torch, the electrodes, and the working environment. For the experiment, we propose to use three to five plasma torches, enabling us to obtain plasma of different chemical composition and easily tunable to the treatment of various types of waste [17, 18].

The inorganic fraction of the feedstock melts and forms a liquid slag that is periodically or continuously tapped out at the bottom of the reactor [19, 20].

The organic part of the feedstock is decomposed and gasified into syngas. The syngas travels up from the high-temperature zone into the upper low-temperature zone, heating the incoming feedstock, and exits at the top. The syngas, essentially CO and H_2 created in the plasma-treatment process, is extracted from the reactor and passed through a syngas cooling and cleaning system. The heat extracted from the gas during the gas cooling process can be reused with an appropriate system. Once the syngas is clean it can be combusted for electricity generation using a steam cycle, gas turbine cycle, combined cycle, gas engine, etc. The syngas can also be used for chemical production, such as hydrogen and methanol production [16]. To ensure performance optimization, the plasma-treatment system must be monitored by controlling several parameters including feed rates, temperatures, plasma power, and the entire slag removal process.

3. Results and discussion

3.1. Economic vision for the amount of waste in Makkah

The treatment of solid waste in crowded regions, especially during the two Arabic calendar months of Ramadhan and Zulhijjah (equivalent to the ninth and the twelfth month in the Gregorian calendar) is a challenging task for the Makkah authorities. The religious rituals of Muslims are performed in limited spaces in the regions of Al-Haram and Al-Masha'ir. The most crowded period within a short time occurs between the 8th and 13th Zulhijjah Arabic month (12), creating huge amounts of waste. Then, the disposal of waste becomes very important in order not to hinder or pose problems to the pilgrims.

The economic vision will focus on the waste of Al Masjid Al-Haram (the holy mosque of Muslim the community), its surroundings, and the Al-Masha'ir regions (Mina, Muzdalifah, and Arafat), which are the areas where the rituals of the Muslim religious pilgrims are performed.

The waste quantity data were made available by the local holy Makkah municipality, regarding the general administration of cleanliness, and the quality management and performance evaluation. Table 1 shows the total amount of waste for all months, as well as the total amount of waste with the exception of the month of Zulhijjah and Ramadhan for the Arabic year from 1414 to 1436 (2004 to 2016) [21].

The amounts of solid waste were calculated without slaughterhouse (SGH) waste, refuse-derived fuel (RDF), car tires, or slag, respectively, because they are all present in a very high percentage through the pilgrimage seasons and need to be considered. They will be discussed separately in our future work. Figure 4 shows the amount of waste in tons per year in the whole city of Makkah during the last twelve years. The results indicate that the average generation rate of waste reached 750 thousand tons in 1414 and up to one million tons in 1436. As shown in figure 5, whereas waste during the month of Ramadhan (9) and ZulHijjah (12) reached 60 and 100 thousand tons in year 1414 , it is up to 100 and 140 thousand tons in year 1436, respectively [22].

Table 1. Total waste for all months and total waste except for the months of Ramadan (9) and Zulhijjah (12) in tons for the Arabic year from 1414 to 1436.

	ARABIC YEAR FROM 1414 TO 1436 (2004 to 2016)				
Arabic Months	1414	1418	1422	1426	1436
Muharram (1)	59 566 Ton	49 177 T	60 528 T	60 621 T	48 513 T
Safar (2)	58 904 T	46 257 T	54 901 T	77 429 T	81 193 T
RabiulAwwal (3)	47 578 T	41 828 T	52 961 T	78 285 T	86 307 T
RabiulAkhir (4)	45 550 T	43 337 T	56 551 T	79 791 T	85 911 T
JamadilAwal (5)	41 680 T	50 334 T	55 830 T	79 300 T	78 537 T
JamadilAkhir (6)	46 424 T	50 450 T	57 121 T	79 448 T	83 038 T
Rejab (7)	42 948 T	52 226 T	61 729 T	82 517 T	83 115 T
Shaa'ban (8)	47 361 T	49 454 T	59 192 T	74 196 T	79 808 T
Ramadhan (9)	51 164 T	59 662 T	78 596 T	93 498 T	88 948 T
Shawal (10)	50 754 T	48 263 T	65 234 T	83 163 T	75 744 T
ZulQaedah (11)	57 428 T	66 786 T	72 989 T	77 724 T	78 534 T
ZulHijjah (12)	91 319 T	113 363 T	129 776 T	104 796 T	140 691 T
Total waste for all months	640 676 T	671 137 T	805 408 T	970 768 T	1010 339 T
Total waste except months of Ramadan (9) and Zulhijjah (12)	498 193 T	498 112 T	597 036 T	772 474 T	780 700 T

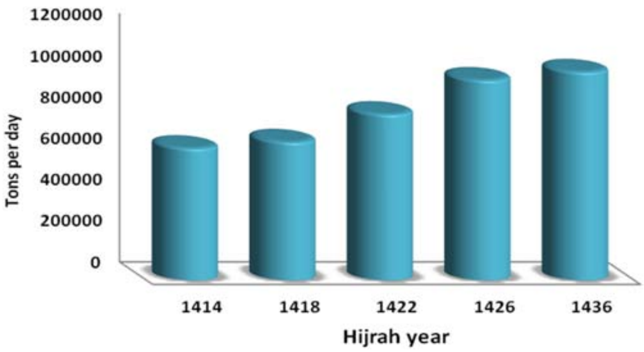

Figure 4. Amount of waste per year in Makkah from 1414–1436.

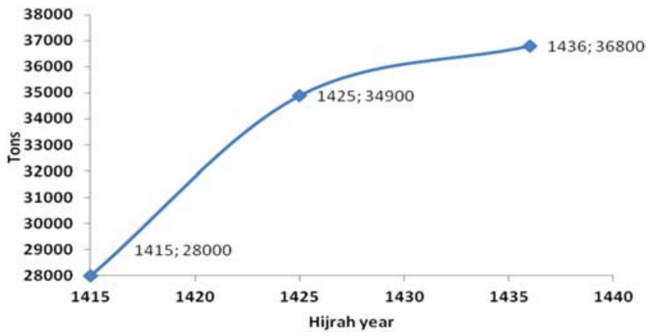

Figure 6. Amount of collected waste in tons from the Masha'ir region during Zulhijjah month, between Hijrah year 1415 and 1436.

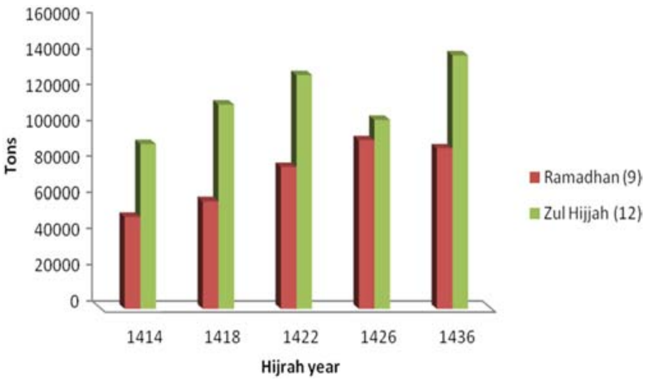

Figure 5. Amount of waste in Makkah from 1414–1436 for the months of Ramadhan and Zulhijjah.

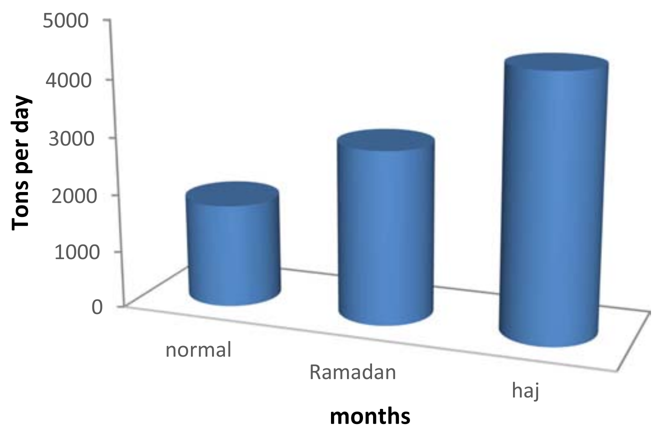

Figure 7. Amount of waste in TPD on normal days during Ramadan and Hajj.

Furthermore, figure 6 shows the waste of the important and crowded three regions of the city of Makkah represented by Mina, Muzdalifah, and Arafat, for one month only of the year (ZulHijjah (12)), whereas the quantity of waste reached 28 thousand tons in year 1415, and up to 36 800 thousand tons in year 1436 [23].

The results indicate that the average per capita waste generation rate for pilgrims and local people in the Arabic year 1436 (2015) was 2.05 kg per day. Figure 7 shows that the amount of waste received at the landfill (LF) increased from 1800–2000 tons per day (TPD) on normal days to 3000 TPD during Ramadhan and 4500 TPD during Hajj, 1436.

Figure 8 shows that the composition of the waste through year 1436 (2015) can be mainly classified as: 39% plastics, 19% paper, 1% aluminum, 17% food waste, 2% nappies, 12%

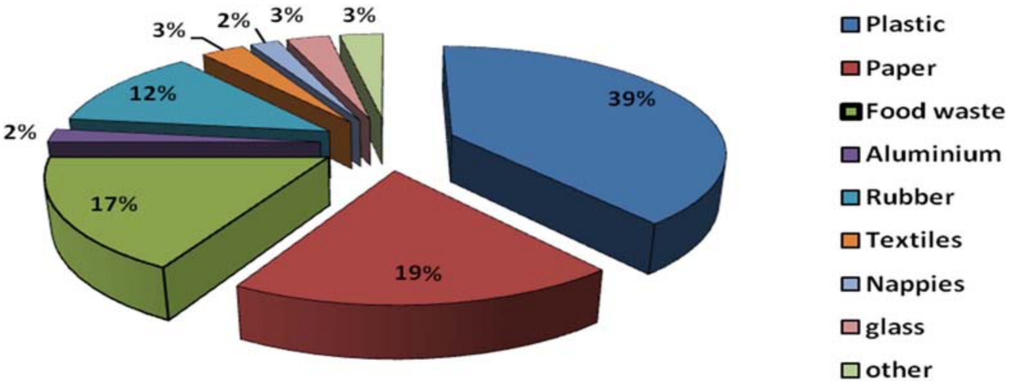

Figure 8. Composition of waste from Makkah through 1436.

Table 2. Comparison between the use of plasma treatment, LF, and ICR for the treatment of the accumulated organic waste.

Items	Plasma treatment	LF	ICR
The nature of the process	Reduces oxidation	Carbon dioxide gas is built up in the LF in the first few months as a result of the decomposition of biological waste by air, but with the passage of time the oxygen in the LF decreases, and then the process of decomposition begins	Oxidation is greater than the conventional measurements and does not produce complete combustion
The process temperature	1500 °C–5000 °C	The larger the depth of the LF , the larger the amount of waste, and particularly in the lowest depths the temperature increases	850 °C–1200 °C
Energy product	Carbon dioxide, and water, methane and hydrogen in the form of heat from industrial gas after cooling	Carbon dioxide as a result of the decomposition of biological waste, and with time resulting in methane production to a rate of almost 40%–60% of the so-called LF gases. In addition to hydrogen sulfide gas, fumes of 'PVC' and dioxin gas are produced and other toxic gases, which with time seep into the soil outside the LF area	Carbon dioxide, water, and waste that cannot be recovered by heat
Energy recovery efficiency	Full decomposition, with high total energy recovery	Without any recovery of the energy released	Released without any energy recovery as the excess air leads to more piles of waste heat
Flexibility of use of energy product	Increasing the use of gas and gas turbines to produce electricity using the produced syngas	Wasted heat is not utilized and emitted to the atmosphere	None
Emission	Non-existent; air pollution limits	Air pollution due to gases emitted	Emission much larger than for plasma treatment and LF without adhering to the required air pollution controls
Waste after process	Inert slag can for, example, be used for construction and to insulate buildings where the value is from 10%–15% of the original amount of waste	However, accumulate over time and degrade and damage the surrounding environment in the atmosphere as a result of the escalation of the fumes through self-combustion	Tar and ash represent almost 30% of the original size
Pollutants	Low levels of nitrogen oxides, and tar, and carbon oxides and other pollutants, consisting of slag	With time, the rising gases, such as methane become highly combustible, in addition to scientific studies that proved that they produce disease-causing cancers	Nitrogen oxides and sulfur oxides, and fly ash, blowing ash, and heavy metals

Table 3. Gas ratios, moisture, and the amount of carbon and hydrogen, which are contained in each component of the primary waste components.

Waste Category	C%	H%	O%	N%	S%	Ash	Moisture (% weight)	Largest carbon and hydrogen content (highest heating values) (HHV) (MJ/T)
Paper	43	6.0	43.8	0.36	0.17	6.3	24%	13 500
Wood	49.5	6.0	42.7	0.2	0.1	1.5	2%	16 700
Food waste	45.4	6.9	32.2	3.3	0.32	11	65%	7250
Textiles	55	6.6	31.2	4.6	0.15	2.5	27%	16 050
Plastic	76.3	11.5	4.4	0.26	0.2	5.3	13%	33 270
Rubber	78	10	0	2	0	10	2%	31 300

rubber and leather, 3% glass, 3% textiles and clothes, and 4% other [24].

These massive amounts, and types and forms of waste require the development and use of modern methods for the treatment of waste that is different from the traditional methods, such as LF, recycling, combustion, and burial of waste, which lead to the loss of a great wealth of organic materials that represent 60% of the value of waste and furthermore cause health and the environmental problems. The conversion of waste into energy through plasma treatment is proposed as an alternative and renewable energy source.

3.2. Environmental vision of plasma-treatment technology

3.2.1. Facilities for the treatment of waste. In Makkah, plasma treatment as a way to get rid of waste streams is preferred more than other waste-to-energy methods, because it converts waste into useful energy, thereby providing benefits, such as a low proportion of the material to be buried, access to electric energy through plasma technology, and treatment of different types of waste at the same time.

Table 2 shows the comparison (for organic waste) between the plasma-treatment method, incineration (ICR) and LF [21], with the following parameters: the nature of the process, the process temperature, energy product, energy recovery efficiency, flexibility of use of the energy product, emission, waste after the process, and pollutants. ICR and LF are still used in Makkah, and the environmental comparison with PTP shows that the higher energy costs of the plasma-treatment method may be offset by the lower costs of treating the remaining slag and gas produced.

3.2.2. Energy recovery analysis using modeling of the plasma treatment of waste streams. Energy recovery analysis for the parametric study of different waste streams was carried out in co-operation between the Institute for Hajj and Umrah Research, Kingdom of Saudi Arabia, and the Institute of Plasma Physics (IPP), Czech Academy of Sciences, to assess the efficiency and input energy required for the plasma treatment of a few categories of waste streams. Table 3 provides an ultimate analysis of waste categories of waste streams, which will be analyzed in order to achieve the highest energy recovery from a plasma-treatment plant. Solid waste should be pre-processed and the groups of waste with the highest heating value (i.e. those with the largest carbon and hydrogen content) should be sent to the plasma-treatment plant [21, 22].

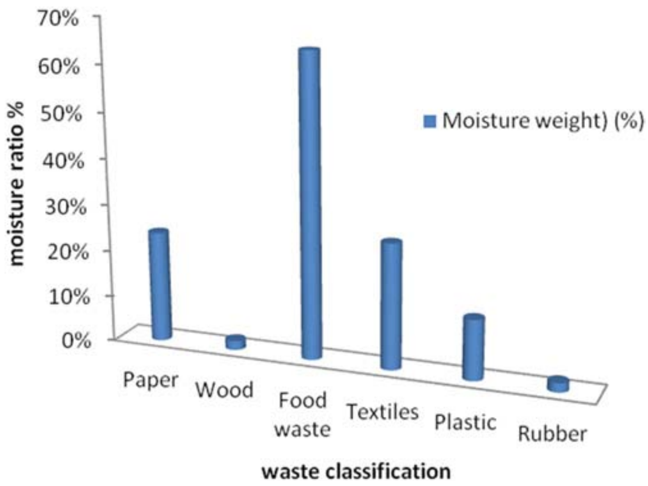

Figure 9. Moisture content in each type of primary waste material.

The plasma-treatment process consists of the complex conversion of the organic compounds into a mixture of gaseous species, where there are many chemical reactions including the transformation of the feedstock into intermediate chemical species followed by transformation into final products. The plasma-treatment reaction with air is as follows [23]:

$$CH_xO_y + wH_2O + m(O_2 + 3.76N_2) \rightarrow n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2 + n_7C$$

where the solid waste is represented by CH_xO_y and the moisture content of the waste is represented by H_2O, and where m and w are the moles of air and moisture (water), respectively. The moles of the various plasma-treatment products vary from n_1 to n_7.

The above equation shows that any organic compound in the waste streams, in the presence of air and temperature, will be converted into the seven products shown. CO and H_2 are the two main products of interest in the syngas, and CH_4 to a lesser extent.

Figure 9 shows the moisture content results for different feedstock. Rubber and wood have a lower percentage of moisture than the other items, while food waste has a high moisture content. Furthermore, the treatment of plastics or rubber produces the largest energy recovery per ton of input. They do require more electricity input than that required for

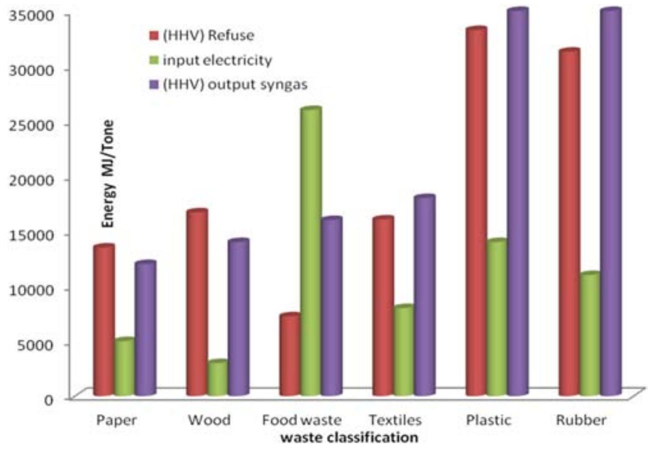

Figure 10. Type and quantity of energy entering and leaving each type of waste material.

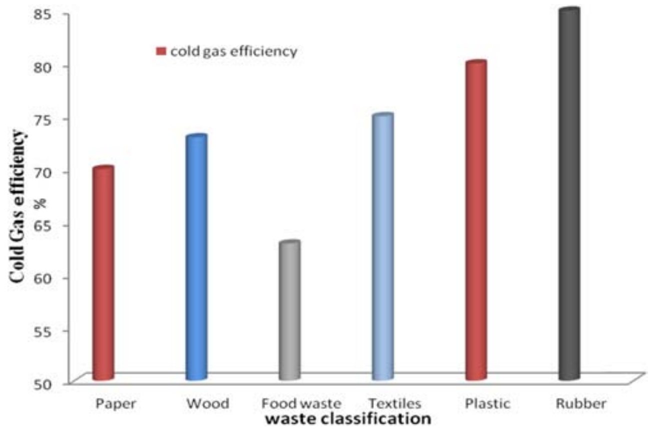

Figure 11. Cold gas efficiency using plasma treatment on various waste stream feedstock.

wood or paper, but due to their higher carbon and hydrogen content the HHV are higher for plastic or rubber [23], as shown in figure 10.

More information on the energy calculations by Mountouris *et al* can be found in [24]. A model called 'Gasif Eq' has been developed for the plasma-treatment thermodynamic and chemical equilibrium processes. The model states that the efficiency of the production of syngas from a plasma-treatment process is obtained by dividing the lower heating value (LHV) of the produced syngas by the sum of the LHV of the waste feedstock and the electricity used to power the plasma-treatment torches. The formula for the efficiency, called the cold gas efficiency is given as follows:

$$\eta_{\text{cold}} = \dot{m}_{\text{syngas}} * \text{LHV}_{\text{snygas}}/(\dot{m}_{\text{waste}} * \text{LHV}_{\text{waste}} + P_{\text{Plasma}})$$

where $\dot{m}$ is the mass flow rate of syngas and solid waste and the LHV due to their lower carbon and hydrogen content, P_{plasma} is the electrical power for the plasma torch. The cold gas efficiency η_{cold} is the ratio of the heating value of the produced synthesis gases $\text{HHV}_{\text{syngas}}$ to the heating value of the waste input $\text{HHV}_{\text{refuse}}$ plus electricity used by the plasma torches P_{plasma} [25].

By applying the 'Gasif Eq' model to our plasma-treatment system, the cold gas efficiency η_{cold} for various waste feedstocks can be determined, as shown in figure 11. Looking back at figure 10, one would take the value of the third bar of the $\text{HHV}_{\text{syngas}}$ divided by the sum of the values of the first two bars for each feedstock ($\text{HHV}_{\text{refuse}}$ plus P_{plasma}) to arrive at the cold gas efficiency [26].

When the syngas product exits the plasma gas furnace, it consists of hot gases that need to be cooled and then treated to remove air pollutants. The hot gases could be run through a heat recovery steam generation heat exchanger to recover some additional useful energy in the form of steam that could be used for district heating or to run a steam turbine to generate electricity.

4. Economic vision of plasma-treatment technology

4.1. Cost and profit for the treatment of solid waste by plasma treatment

Based on the previously-mentioned amount of waste in the city of Makkah (tons/year/day), the economics of the plasma-treatment processes and the analysis of energy recovery are being analyzed. There are many variable parameters, such as regional characteristics, type of waste, capacity, the ability to treat it in the plasma furnace, the number of workers, the number of hours and amount of electricity required, the percentage of syngas extracted for each type of waste, and the utilization of the output slag. These and other parameters are listed in a worksheet (appendix).

For the total waste streams in Makkah, two plasma-treatment reactors with the capacity 100 TPD will be required, one in the Al-Masha'ir region (Mina, Muzdalifah, and Arafat) and the other serving close to the area of the holy Kaaba region.

The cost for the construction of a 100 TPD plant is in the range of 35 million EUR. This includes operation costs, insurance, workers, electrical energy consumed, general expenses, such as fringe benefits, the cost of safe maintenance, and training. Also *per diem* and travel expenses of trainees, as well as the transport costs of the plasma-treatment reactors from their country of origin.

The various costs include maintenance, electricity, and chemicals, as well as the cost of the water used in the processor, which amounts to up to one million EUR/year [27, 28].

Table 4 shows the characteristics of a plasma-treatment thermal plasma processor with a capacity of 100 TPD of waste, and also shows that the amount of thermal plasma-energy consumption was estimated at 0.447 MWh/ton with loss of heat from the liquid gas (loss of efficiency) by 10% and 7% through the walls of the system; so that it can restore energy by using steam turbines [29–31].

The electrical power required for the plasma-treatment process is estimated at 5000 kW (2000 kW used for the operation of the system and 3000 kW sold), taking into account the fact that: (1) the processing capacity of solid

Table 4. Characteristics of a plasma-gasification processor for the treatment of waste with a capacitance and operational capacity of 100 TPD [32, 33].

Items	The actual value for 100 TPD
The amount of thermal plasma-energy consumption	0.447 MWh/ton
Heat loss of liquid gases	10%
Heat loss through system walls	7%
Energy recovery	Through the use of steam turbines
Energy generating system	5000 KW
Electrical energy consumed	2000 kW
Electric power sold	3000 kW
The number of working days in a year	330 d
Hours of operation per day	24 h
Number of electricity sales	23.8 MWh/year
Unit cost of electricity sales	14 euro cent/kWh
Profit from the sale of electricity	3.27 million EUR/year 30 MWh/year × 10.9 euro cent/kWh
Profit from solid-waste treatment	4.99 million EUR/year(100 TPD × 330 d/year × 151 EUR/ton
Gross profit per ton of municipal solid waste (waste streams)	200 EUR/ton gross profit per ton of solid waste per year (6.6 million EUR/year)

waste is 100 TPD, (2) the sale of electricity amounts to 23.8 MW at 0.18 EUR per kWh, (3) the profit from the sale of electricity per year is estimated at 3.27 million EUR and the estimated profit from the solid-waste treatment amounts to 6 million EUR per year, and (4) the gross profit per ton of solid waste totals 8 million EUR per year.

4.2. Advantages and benefits of plasma-treatment technologies [34, 35]

1- LF contributes to global warming due to the release of CH_4. Therefore, plasma treatment is a more environmentally friendly option.
2- Getting secondary useful products (energy, fuels, and chemical raw materials) from organic vegetable waste, organic biological waste, synthetic waste (polymers, plastics), petrochemical waste, low-grade mineral fuels, municipal and industrial waste (non-toxic).
3- Environmentally safe disposal, recycling of toxic (including POPs), medical, radioactive, and military waste into an inert form.
4- Ecological cleanliness where waste products can be processed without preliminary sorting; moreover, the absence of harmful emissions, such as dioxides.
5- The inert alloyed slag, which can be used as building materials.
6- Opportunity to convert organic waste products into combustible gases, which can be used for technological purposes. For example, syngas with high calorific value and high hydrogen content is produced.
7- Opportunity to produce thermal or electric energy with high energy density and high thermal transfer efficiency.
8- Reduction of reactor volume, and furthermore, better control of exhaust gas composition (plasma torches are an external heat source).
9- Reduction of the production of tars (organic compounds with high molecular weight).

5. Conclusions

The important potential for renewable plasma-energy sources is presently not taken into account in Saudi Arabia. For Saudi Arabia to be the first Arab country to develop a national policy to support renewable plasma-energy sources, it could substantially contribute to the sustainable production of fuel and electricity.

The technical and environmental advantages of the waste treatment by plasma in Makkah are substantial. Plasma-treatment results in secondary products (energy, fuel, and chemical raw materials) from organic waste, bio-organic wastes, industrial waste (polymers and plastics), and waste from petrochemicals and fuel, which is considered the most important benefit for the kingdom. Furthermore, compared to other waste-treatment techniques, the size of the reactor is reduced and the control over the composition of the exhaust gases is improved.

A sustainable future for Saudi Arabia can eventually be achieved through the use of advanced technologies for a diversity of alternative energy sources. Saudi Arabia is seeking, through the use of modern science and research, and through industrial partnerships and technical development, to develop a new generation of sustainable energy production. The PTP for the treatment of waste streams can convert 3–5 thousand tons of waste per day into up to 120 MW of electricity, enough to meet the electricity needs of ten thousand households. The application of PTP in waste treatment in Saudi Arabia may provide between 50% to 75% of the costs of setting up power plants in the future.

The present article presents the first stage of the PTP in Makkah in the pilgrimage seasons, which consists of five stages: (1) study and treatment of waste streams, (2) SGH waste treatment, (3) treatment of RDF, (4) treatment of car tires and (5) treatment of slag (the fifth stage associated with each stage from the four previous stages).

Appendix. Important key data required for the design of the plasma-gasification project in Makkak

1- Amount of different waste:
  a- Amount of waste from raw material............................. t/year.
  b- Amount of waste for rubber material............................. t/year.
  c- Amount of waste for glass material............................. t/year.
  d- Amount of waste for waste stream material.............. t/year.
  e- Amount of waste for plastic material............................. t/year.
  f- Amount of waste for wooden material............................. t/year.
  g- Amount of waste for paper and carton material.............. t/year.
  h- Amount of waste for textile material............................. t/year.
  i- Amount of waste for aluminum material.................... t/year.
  j- Amount of waste for nappy material............................. t/year.
  k- Amount of waste for SGH material............ t/year.
  l- Amount of waste for RDF material......... t/year.
  m- Amount of waste for tire material............................. t/year.
  n- Amount of waste for asbestos material....................... t/year.
  o- Amount of medical material....................... t/year.
2- Working hours of uninterrupted operation fund—8000 h/year.
3- Classification of input waste material...... t/year/month/day as: organic waste; non-organic waste; industrial waste; hazardous waste; biomass (straw, shavings, sewage sludge).
4- Planned output of electric energy MW/h—thermal energy MW/h of steam parameters temperature (°C), MPa pressure hot water entering the system (°C/°C) return branch; bio jet fuel.
5- Properties of main building of the project (Size W × L (m) area (m$^{2)}$; industrial area; agricultural land; compliance of project and site development plan in the selected region of the project availability of land for trucks.
6- How to remove the material input and the distance between the LF and the reactor (km).
7- Supply networks as: gas supply pressure MPa parameters—installed capacity power supply, transformer (j/n), parameters.
8- Technological water yield as: water analysis; sewerage system; wastewater treatment plants.
9- The incoming parameters of wastewater, the measurement/registration (of the treatment plant) are subject.
10- Power dissipation.
11- Distance from the property line (km).
12- Definition of input materials.
13- The quantity specified changes in summer and winter.
14- Calorific value of minimum waste (MJ/kg).
15- Physical properties of the waste.
16- Waste composition—basic information.
17- Waste elements in the dry mass (mass%) as: H%-C%-O%-N%-S%.
18- Combustible component.
19- Unsorted waste energy content (calorific value)—MJ/kg.
20- Sorted waste energy content (calorific value)—MJ/kg.
21- Moisture max. values (%) and components (mass%) as: paper%; cardboard%; cardboard%; non-organic waste-%; wood%; textile%; rubber%; plastic%; organic waste%; glass%; metal%; soil%.
22- Elemental composition of the waste (% dry mass fractions)—Examples: C –N-S –H-O-Cl and ash content%.
23- Burning waste content in mass% of finished fabrics.
24- Content of incombustible waste (ash) in mass%.
25- Ash composition (wt%) as: Na%-K%-Ca%-Mg%-Fe-%-Si%.
26- Climatic conditions.
27- Average annual temperature of the environment; relative humidity.
28- Average summer temperature of the ambient air (°C).
29- Average winter temperature of the ambient air (°C).
30- Maximum ambient temperature (°C).
31- Minimum temperature of the environment (°C).
32- Mean atmospheric pressure.
33- Temperature of the technological water (°C).
34- Height above sea level in meters above sea level.
35- Average annual rainfall (mm).
36- Average temperature and the width below the ground of the LF area.
37- Prevailing wind direction predominant flow directions … with average speed (m/s).
38- The kind of project (strategic project or academic and scientific project).

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