ARTICLE IN PRESS

Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Prospective application of municipal solid wastes for energy production in Portugal

Sandra Teixeira [a,b], Eliseu Monteiro [b,c], Valter Silva [b], Abel Rouboa [a,b,*]

[a] University of Trás-os-Montes and Alto Douro, Vila Real, Portugal
[b] INEGI/Faculty of Engineering, University of Porto, Porto, Portugal
[c] C3i – Interdisciplinary Center for Research and Innovation, Polytechnic Institute of Portalegre, Lugar da Abadessa, Apartado 148, 7301-901 Portalegre, Portugal

HIGHLIGHTS

- MSW collection and disposal are a major problem of urban environment.
- Portugal is facing multiple problems and improving the MSW management system.
- Gasification offers the most attractive solution to both waste disposal and energy problems.
- Plasma gasification seems to be validated but the economic viability must be proven.

ARTICLE INFO

Article history:
Received 22 November 2013
Received in revised form
1 March 2014
Accepted 1 April 2014

Keywords:
Municipal solid wastes
Incineration
Gasification
Environmental policy

ABSTRACT

Municipal solid waste (MSW) collection and disposal is a major urban environment issue in the world today. MSW management solutions have to be technologically feasible, legally and socially acceptable and environmentally and financially sustainable. European policy is pushing for a rational management of natural resources; a promising technological perspective today is waste valorisation, a process that involves sorting at the source, combined with material recycling and waste-to-energy conversion. In this paper, we analyze the evolution of the Portuguese MSW management system, criticize the environmental policy issues for MSW management in Portugal and identify weak points in the criteria used for the technologies selection. Portugal is facing multiple problems with MSW management and is attempting to tackle them by passing legislation in order to improve the performance of waste management systems. At the technological level, gasification increasingly presents as an efficient and viable alternative to incineration. Gasification is a waste-to-energy conversion scheme that offers an attractive solution to both waste disposal and energy problems. Waste gasification by plasma has been validated but the economic viability of this technology must be proven before to be accepted by the industry.

1. Introduction

Population growth, technological development and increasing consumerism have led to high consumption of resources. Consequently, there is increasing production of waste, and the need to develop an integrated management of municipal solid waste (MSW).

The implementation of the first strategic plan for municipal solid waste (PERSU I) marked a turning point in the field of MSW management in Portugal. This document defined the application of a hierarchy of principles based on the strategic foundations of the European Union (MAOTDR, 2007).

MSW management activities contribute to the generation of greenhouse gas and consequently to the climate change problem. Landfill waste decomposition contributes greatly to the formation of these gases. Another environmental problem associated with MSW management systems is the potential generation of dioxins and furans associated with incomplete combustion of wastes (Smith et al., 2001).

Despite some strategic plans of MSW management having been adopted, several studies have shown the lack of data and inconsistencies in a number of results regarding MSW management (Magrinho et al., 2006).

Nowadays, in Portugal there is official data thanks to the strategic plans PERSU I and PERSU II. The wide variety of processes and technologies for MSW treatment and the various possibilities of combining them have given rise to various structures and

* Corresponding author. Tel.: +351 259 350 000; fax: +351 259 350 480.
E-mail address: rouboa@utad.pt (A. Rouboa).

http://dx.doi.org/10.1016/j.enpol.2014.04.002
0301-4215/© 2014 Elsevier Ltd. All rights reserved.

solutions for MSW treatment. The optimal solution for MSW treatment is not yet fully established (Magrinho et al., 2006).

In this paper the main objective is to assess the influence of MSW strategic plans and legislation on the wastes management system and infrastructures facilities. The second goal is to analyse the various technologies associated with MSW management systems.

2. Materials and methods

According to the EU Directive 1999/31/EC, municipal waste means waste from households as well as other waste which, because of its nature or composition, is similar to waste from households. This contains household residues, agricultural residues, commercial residues and those resulting from civil construction. The composition of these residues is extremely variable; it is influenced by factors such as geographic location as well as season of the year. In this type of residue alimentary remains, sanitary residues, paper, plastic, glass, wood, cement and metals can be found. The responsible entities for collecting MSW must meet several requirements, in agreement with the European implemented directive 2008/98/EC.

Nowadays, the base for any waste management system is to reduce, recycle and reuse. Until the end of the 1990s, closing open dumps was the first process adopted for MSW management in Portugal. Since then, MSW management has developed towards partial treatment and disposal options such as recycling, composting, and incineration with energy recovery. However, landfills were the dominant option for MSW disposal in Portugal up to 2002.

Since 1997 when the PERSU I was issued, the number of systems for municipal solid waste recovery and treatment (SGRSU) decreased from 40 to 23 in 2010. A progressive merger of systems contributed to this reduction, which was imposed by the goals of PERSU II, which favoured the aggregation of systems to maximize waste recovery using the existing infrastructures (APA, 2010). Nowadays there are 23 SGRSU in mainland Portugal, 12 are multi-municipal and 11 intermunicipal. Table 1 describes the SGRSU in 2010 and their characteristics in detail, including their infrastructures.

Thus, in mainland Portugal 2010 there were 34 landfills, 29 sorting centres, 81 transfer centres, 190 ecocentres, 37,971 ecopoints, two energy recovery centres, 11 organic recovery facilities and seven mechanical biological treatment facilities (MBT). This number of management systems is not yet ideal for the implementation of energy recovery, organic recovery and MBT facilities articulated with the PERSU targets.

A scheme of the Portuguese MSW management organization as described in Fig. 1 involves collection, storage, treatment and disposal. MSW collection includes selected wastes and unselected wastes. The unselected wastes are under the responsibility of each municipality, although the selected wastes can be under the responsibility of the municipalities, the MSW management system and private companies (Magrinho et al., 2006). The ecocentres and ecopoints are devoted to selected wastes. Ecopoints are devoted to separate collection based on the use of different containers for glass, paper/ cardboard, and plastic/metal, placed together at ecopoints preferably located on public thoroughfares and strategic points near shopping malls, schools, parks, pools, sport complexes, markets, fairs, etc. Ecocentres are sorting centres, where the selected wastes from the ecopoints are delivered for recovery.

In addition to the materials referred to above as part of mechanical recycling there are other specific fluxes of waste (used oils, batteries, electrical and electronic wastes, construction and demolition residues, end-of-life vehicles and used cooking oil). Transfer stations provide the facilities required for unselected wastes when landfills or MBT station are far away. Therefore, unselected collection can be understood as the sum of landfill wastes with energetic and organic refuse. The selected collection includes ecopoints and door-to-door collection with ecocentres and biodegradable municipal waste collection (APA, 2010). MBT plants are designed to process mixed household wastes as well as commercial and industrial wastes. The MBT tolerates recycling paper, metal, plastic and glass. It can produce refuse-derived fuel (RDF) or stabilize the biodegradable materials by composting or anaerobic digestion. The RDF can be further used as alternative fuel in cement kilns or incinerated to produce energy. The ash formed during incineration contains mostly inorganic constituents of the wastes and is often landfilled (Stantec, 2011).

Table 1
SGRSU and infrastructure existing in mainland Portugal in 2010 adapted from APA (2010).

System	Region	Inhabitants	Infrastructure							
			Landfill	Sorting centres	Transfer centres	Ecocentre	Ecopoints	Energy recovery centre	Organic recovery centre	MBT
Valorminho	North	77,704	1	1	1	2	470	–	–	–
Resulima		322,096	1	1	1	2	912	–	–	–
Braval		290,508	1	1	1	2	1131	–	–	–
Resinorte		956,763	5	4	8	15	3282	–	1	–
Lipor		984,047	1	1	–	21	3565	1	1	–
Valsousa		337,609	2	3	2	8	756	–	–	–
Suldouro		441,485	1	1	–	4	1489	–	1	–
Resíduos Nordeste		143,777	1	–	4	14	580	–	–	1
Ersuc	Centre	956,808	3	2	6	7	3557	–	–	1
AMR		349,720	1	1	3	19	1334	-	1	1
Reisistrela		202,761	1	1	8	14	625	–	1	–
Valnor		272,195	2	1	7	13	1346	–	1	–
Valoris	Lisbon and	307,265	1	1	3	4	984	–	–	1
Valorsul	Tejo Valley	1,610,786	2	2	6	8	5537	1	1	–
Ecoleziria		127,058	1	–	2	4	336	–	–	–
Resistejo		209,587	1	1	3	9	1201	–	1	–
Amtres		831,178	1	–	3	2	4406	–	–	1
Amarsul		778,028	2	2	1	7	2378	–	1	–
AMDE	Alentejo	155,268	1	1	4	7	652	–	–	1
Amagra		115,417	1	1	4	7	505	–	–	–
Amcal		25,506	1	1	2	4	111	–	–	1
Amalga		95,763	1	1	4	5	380	–	–	–
Algar	Alvarve	450,484	2	2	8	12	2404	–	2	–

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002

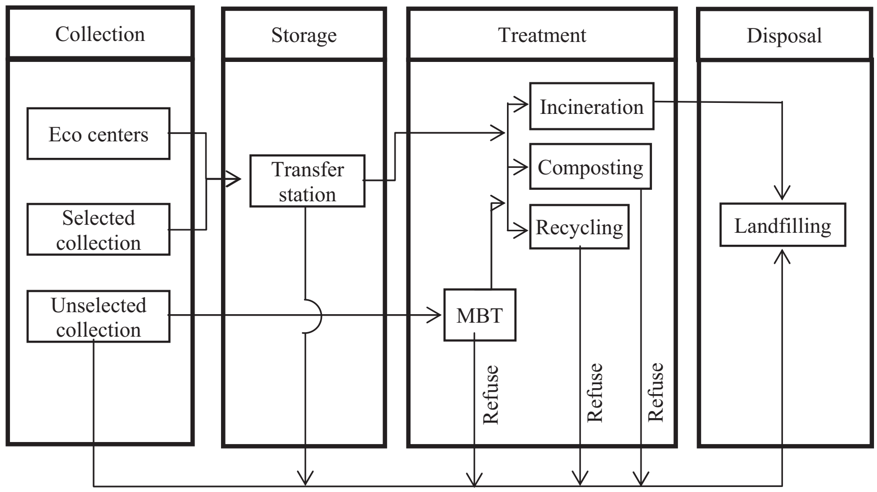

Fig. 1. Schematic overview of a conventional waste management system.

Biodegradable wastes can be converted into compost, carbon dioxide and water under an aerobic process. Composting is the common process for organic recovery of the wastes into soil conditioner. The remaining non-biodegradable wastes are recycled to recover materials for new products (Stantec, 2011).

Wastes from unselected collection as well as waste coming from MBT, incineration plants, composting and recycling refuse are disposed of in landfills. Landfilling is the last treatment to be adopted because it causes severe environmental impact from greenhouse gases released into the atmosphere and also from leachate percolating into ground water. To help minimize the environmental impact, the biogas generated by anaerobic reactions can be used as fuel to produce heat and power (Magrinho et al., 2006).

2.1. Legal framework and policy

Until the 1970s, even in Europe there was little legislation related to waste issues. Only in the last three decades has MSW become a major problem and a major public concern.

In 1975, with the establishment of Directive 75/442/EEC of the European Economic Community, the first definition of waste was created. Since then the definition has undergone significant changes.

In 1994, the Directive 94/62/EC concerning packaging and packaging waste, established the principles and the regulations that must be applied to their management in order to reduce their production, ensuring the reuse of used packaging, recycling and some other forms of packaging waste recovery and, consequently, reducing the amount requiring final disposal, assuring a high level of environmental protection. At national level, in 1994 a set of laws and several SGRSU were legally created in Portugal.

In 1996, Ordenance n°15/96 was introduced, predicting the types of waste disposal and recovery operations including energy recovery. In July 1997 the PERSU was created and defined with the following objectives:

- the total eradication of open dumps in Portugal;
- the construction of multi-municipal and intermunicipal systems for MSW management;
- the construction of waste treatment infrastructure (recovery and disposal).
- the implementation of selective collection, with ecopoints and ecocentre installations.

In general, all these objectives were intended to create sustainable development for MSW management for the period from 1997 to 2006. This strategic plan allowed assessing the problem of waste management in Portugal. A diagnosis was made and the priorities were clarified: the option by reduction preventive tools, re-use and recycling, and the creation of treatment and final disposal systems were the priority choices of the plan's options. In 20th of September 1997, Decree-Law n °366-A/97 came into force transposing Directive 94/62/EC to the national legislative system.

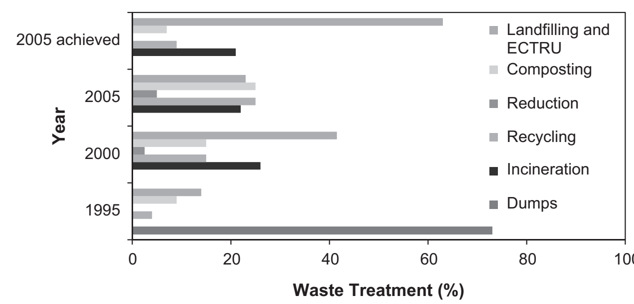

Fig. 2. Projected waste treatment methods according to PERSU I (MAOTDR, 2007).

Fig. 2 shows the waste treatment options in 1995, used to predict the situation in 2000 and 2005. The ECTRU represents the intermediate stations for MSW. Despite the high percentage of waste deposited in landfills when compared to others treatments, the PERSU I had a positive balance. In fact, all open dumps were closed, multi-municipal (which serve at least two municipalities and require a major investment by the State) and inter-municipal (those managed by associations of municipalities) systems for MSW management were implemented, recycling and recovery infrastructure were built and selective collection was implemented (MAOTDR, 2007). However, the performance results were below predictions, namely for the amount of landfill, which amount was almost three times higher than predicted. Only the waste incineration results were close to predicted.

For those reasons and due to new directives (Directive 2004/12/EC, February 11 and Directive 2006/12/EC, April 15) issued, the PERSU I was revised and led to PERSU II in 2007 (MAOTDR, 2007). This second strategic plan (PERSU II) established targets for the period 2007–2016, applied only to mainland Portugal. The main goals of the new strategic plan are as follows:

- a review of PERSU I goals;
- to divert biodegradable MSW from landfill to composting and incineration coupled with MBT;

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002

- a commitment to reduce greenhouse gas emissions;
- the development of recovery technologies, investing in units to produce RDF.

National legislation currently in force concerning MSW management options is the Decree-Law n° 73/2011 of June 17, which was the third change to Decree-law n° 178/2006 of September 5, transposing the Directive 2008/98/EC of the Parliament and the council. The main objectives outlined by this law are:

- strengthening the prevention of waste production by stimulating waste reuse, recycling and recovery;
- to encourage the collection of organic waste;
- to clarify and to review the concepts related with the management of MSW;
- to approve prevention programs with goals at the level of reuse, recycling and recovery until 2020; includes a new 50% re-use and recycling target for waste from households by weight and 70% re-use, recycling and other material recovery including backfilling operations using waste to substitute other materials.
- to outline criteria for changing the status of certain waste materials;
- to introduce the concept of extended producer responsibility.

2.2. MSW technologies

Current MSW management in Portugal is based on three important forms of treatment. A differentiated selection of the MSW collected in the deposition systems promotes the adequate valorization of urban residues, adding value to those residues. In the selection unit, receiving and separation of materials from selective collect, packaging is done for posterior deliver to the recycling industries. The residues, which are non-susceptible to multi-material (recycling or organic) valorisation, are sent to incineration power plants. The resulting combustion gases are neutralized and filtered in high efficiency equipment before emission to the atmosphere. The ashes undergo an inertization process and are then landfilled. The slag is sent to confinement in landfill, and the ferrous scrap is sent to recycling. Technical confinement is the last resource for the MSW management system and is necessary for disposal of residues not subject to valorisation. For this purpose a landfill near the energetic valorisation plant is designed to receive the by-products resulting from thermal treatment process – ashes and slag, as well coarse residues from the upkeep of the energetic valorisation plant.

Organic valorisation is done through the composting of organic residues, with the implementation of itineraries to remove the organic fraction near major producers, markets, shopping malls and large stores, and door-to-door in selective collection areas by removing the organic fraction from domestic residues. The introduction of organic matter into the soil brings numerous benefits by improving characteristics such as porosity, water retention capacity and as an erosion prevention agent, helping to counteract soil compaction, salinization and desertification.

2.2.1. Landfills

In many parts of the world the prevailing treatment for MSW disposal is still landfill, a more economical choice compared to the high cost of other alternative treatments.

The Landfill Directive 1999/31/EC is the most important driver. Article 5 sets out a schedule for Member States to reduce the amount of landfilled biodegradable municipal waste. This reduction was done in stages:

- By 2006, 75% of the amount of biodegradable municipal waste that was landfilled in 1995;
- By 2009, 50% of the amount of biodegradable municipal waste that was landfilled in 1995;
- By 2016, 35% of the amount of biodegradable municipal waste that was landfilled in 1995.

A four-year derogation period exists for those Member States who were landfilling more than 80% of all municipal waste in 1995. This includes various member states including Portugal.

Among the EU member states, Greece, the UK, and Finland are among those most dependent on direct landfilling. In contrast, landfilling accounted for less than 5% of MSW management in Germany, the Netherlands, Sweden, Denmark, and Austria (Eurostat, 2010).

MSW landfills vary significantly from country to country in what concerns MSW management and the pre-treatment before waste disposal. Nevertheless, there are two important common points; the basic design features are alike, and the required post-closure care to ensure protection of human health and the environment is not compromised. These landfills include a waste containment liner system to separate waste from the subsurface environment and a system for the collection and management of leachate and gas, and placement of a final cover after the waste deposition is complete (Fig. 3). The aftercare of closed landfills consists of monitoring the emissions of leachate and gas, and the receiving systems of ground water, surface water, soil, and air, cover maintenance and leachate and gas collection systems. European landfill Directive 1999/31/EC specifies a minimum after-care period of 30 years. Actually some landfill owners/operators include the cost of the 30-year care in their budget, however, the

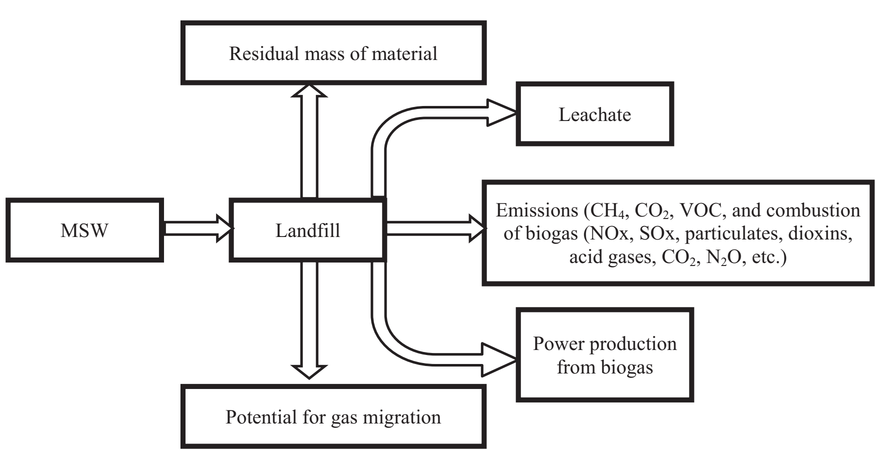

Fig. 3. Schematic representation of landfill inputs and outputs.

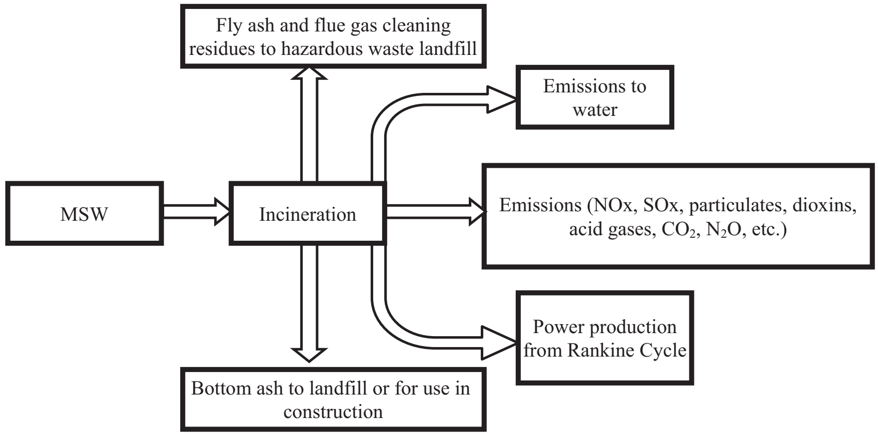

Fig. 4. Schematic representation of incineration inputs and outputs.

lack of criteria and procedures for evaluating landfill completion will make it difficult for regulators to make decisions to end, extend, or reduce the aftercare period (David et al., 2012).

The major benefit from landfill is methane gas generated by anaerobic degradation of the organic contents of the waste (Monteiro et al., 2010). It is a ‘free’ source of energy that is largely cleaner than conventional energy sources. The resulting products from degradation in landfill are carbon dioxide (CO_2), water and heat from the aerobic process, and methane (CH_4) and CO_2 from the anaerobic process. Landfill gas results from three different processes, bacterial decomposition, volatilization, and chemical reactions (Johari et al., 2012).

2.2.2. *Incineration*

Waste to energy incineration is recognized as an effective way to treat MSW (World Bank, 2000) and has been widely applied in many countries (Ecke et al., 2001). For example, in Japan about 80% of MSW is treated by incineration (Jung et al., 2004), and incineration is now the officially prescribed method in Denmark (Heron and Soren, 2007). Waste to energy incineration plants can reduce the original MSW volume by 90% or even 95% if modern incinerators are used (Belevi and Moench, 2000), and steadily generate heat and power.

There are different incineration technologies, such as mass-burn incineration, fluidized bed incineration and incineration of refuse-derived fuel. Of these different technologies, mass burn technology appears to be the most widely used (European Commission, 2002).

For a long time, mass burning of MSW has been considered as a low-cost source of energy as well as an ideal method of waste disposal (Hartenstein and Horvay, 1996). A thermo-combustion plant comprises a combustion chamber, a post-combustion chamber, a heat exchange boiler to recover the energy generated by combustion and an emissions control system. The recovery of MSW combustion energy may be used only for power production or for heat and power generation defined as co-generation (Biniecka et al., 2005).

Incineration can, depending upon the waste composition, handle unsorted municipal wastes as well as wastes from which materials have already been separated. The different incineration technologies mentioned above may make attempts to remove specific fractions of waste from the waste stream. For example, garden wastes may be best treated through composting, both because of their seasonal nature and due to the fact that much of the material (e.g. grass clippings) may have quite low calorific value.

One of the principal constraints on the use of incinerators is public opposition. In some countries people simply do not want to live near these plants owing to their disamenity and emissions of NO_x, SO_x, HCl, particulates, and heavy metals and dioxins associated with the plant. These emissions are known to have negative effects on human health (McKay, 2002).

For dioxins, the case is somewhat controversial. It is important to note that the Waste Incineration Directive 2000/76/EC of the European Parliament and Council of 4 December 2000 impose limit values only to the 17 chlorinated dioxins. Emissions of dioxin-like polychlorinated biphenyls (PCBs) are not included in any of the studies reviewing the health impact of incinerators. Weber and Greim (1997) suggest that the similarity in action of chlorinated and brominated dibenzo-p-dioxins and dibenzofurans appears to imply that environmental and health assessments should be based on molar body burdens without discrimination of the nature of the halogen (characterizing the dioxin). This is important since there are about 5100 halogenated dioxins, as well as polychlorinated dibenzothiophenes and thianthrenes, which are sulphur analogues of the dibenzodioxins and furans, and polychlorinated azobenzenes and azoxybenzenes (the list of potentially harmful chemicals is not a short one).

Ahead description shows that incineration is the one of the most effective treatments of MSW. However, it results in several non-treatable by-products, such as slag and bottom and fly ashes that are a very significant part of the resulting by-products, and the subsequent need for inertization and confinement of these residues in landfills (Fig. 4). It is possible to use the bottom ash in construction applications, although some concerns remain as to the potential impact of this activity. Gas emissions resulting from the combustion of MSW and the required pre-treatment of those gases prior to release in the atmosphere are of great concern. From this perspective there is interest in investigating cleaner alternative forms of MSW treatment. The development of gasification technology and its increasing application, along with environmental restrictions and laws, shows gasification as a viable and cleaner potential alternative for MSW conversion to energy.

2.2.3. *Gasification*

The gasification process of solid waste residues is a complex thermochemical process at high temperatures, producing syngas which can undergo chemical reactions. Thermochemical treatment is carried out by pyrolysis and gasification (Kantarelis and Zabaniotou, 2009).

Pyrolysis or devolatilization is the thermal decomposition of organic material, involving thermal cracking reactions, mass and heat transfer. The result of this decomposition is a liquid fraction and gases containing mainly hydrogen, carbon monoxide, carbon dioxide, methane, solid residue denominated as char (remaining

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002

devolatilized solid residue), and tar (condensable hydrocarbon vapours).

With a supply of additional heat, gasification further breaks down devolatilization products – smaller molecules are formed by the thermal cracking of some of the tar and hydrocarbons in the vapours. The required heat is provided by the partial combustion of a portion of the feedstock in the reactor with a controlled amount of air, oxygen, or oxygen-enriched air. The heat can also be provided from external sources using superheated steam, heated bed materials, and by burning some of the chars or gases separately. The result is a gaseous mixture of hydrogen, carbon monoxide, carbon dioxide and a fraction of light hydrocarbons. The efficiency of the gasification process depends on the type of the gasifier, the type of oxidant and characteristics of the solid waste. The most commonly used oxidants are air, oxygen-enriched air, pure oxygen and steam, depending on the choice of the oxidizing agent, and the resultant syngas also is different in calorific value (Higman and Burgt, 2003).

The specific gasification reactions are those which occur between the devolatilization of the solid waste and the gases, and they can be divided into three individual groups: The water-gas shift reaction, the Bouduard reaction and hydrogasification. The resulting gasification species are in their most reduced form, which means CO instead CO_2, H_2 instead H_2O, NH_3 instead NO, and others (Fig. 5). At low temperatures of about 600 °C, carbon and oxygen exist as carbon dioxide and chars. At high temperatures the carbon dioxide beaks down to form carbon monoxide, however, oxygen exists in the form of CO and CO_2 (Umberto, 2012).

In recent years, gasification technology has undergone great development, with several commercial options for converting MSW to energy. The majority of commercial gasifiers are of the downdraft type, fluidized bed systems and updraft type. The classification of the gasification type depends on the way the feed is made, since it can be from the top, the bottom or the side of the gasifier. Another important aspect is the type of bed; if it is a fluidized bed or fixed bed. The oxidant agent also contributes to the quality of the syngas produced; the most commonly used are air, oxygen-enriched air, pure oxygen or steam. Pressure and temperature are important parameters in the control of a gasification system, as well as the temperature range of the equipment and the method of heating the gasifier – directly heated with gases resulting from partial combustion or indirectly heated with an additional source of heat such as vapour or an inert material. Pressurised gasifiers get better results and promote hydrogen production (E4tech, 2009).

Updraft fixed bed gasifiers have little market appeal since the concentration of tar in the syngas and subsequent need for cleaning is difficult, adding additional costs to the process. In this gasifier the MSW feed is at the top of the gasifier and the oxidant agent is at the bottom, so the feed and oxidant agent move in opposite directions. Some of the resulting char falls and burns to provide heat. The methane and tar-rich gas leaves at the top of the gasifier, the ash falls from the grate and is collected at the bottom of the gasifier (McKendry, 2002). Due to the weak temperature control, sintering can occur so MSW must be sized down to 100 mm diameter particles. Particles stay in the bed until they are discharged. The process has an inefficient heat exchange and low flexibility to change the process variables (Umberto, 2012).

Downdraft fixed-bed gasifiers are more attractive for small scale applications less than 1.5 MWth, yet the problem of tar removal from the syngas still remains. The feed and oxidant agents are both at the top of the gasifier and they move in the same direction (McKendry, 2002). The MSW particle size is up to 100 mm and some of the feed is burned, falling through the gasifier to form a bed of hot charcoal which the gases have to pass through (a reaction zone). Reasonably high quality syngas leaves at the bottom of the gasifier and ash is collected under the grate. Temperature control is very difficult, with the possibility of hot spots. The bed must be discharged at the end of the process. This needs a large surface for heat exchange 20–100 W/m^2K and has low flexibility for changing the process variables (Umberto, 2012).

Bubbling fluidized bed gasifiers can use a variety of feed stocks, and are mostly used in pilot scale and commercial applications on small to medium scales up to 25 MWth. One of the specifications of these gasifiers is that they require a bed of an inert material with a particle diameter between 0.08 and 3 mm. The bed is at the bottom of the gasifier and the oxidant agent is blown upwards through the bed fast enough to agitate the material with a velocity of 1–3 m/s (McKendry, 2002). The feed is from the side with a particle size smaller than 150 mm. The feed mix is partially combusted to form syngas, which leaves at the top of the gasifier. The particle residence time in the bed is considerable – minutes or hours. The operating temperature range is between 550 and 1000 °C, so that melting ash is avoided. The excellent temperature control allows for a large scale of operations and can be pressurized (Umberto, 2012).

Circulating fluidized bed gasifiers are very reliable from the point of view of the feedstock and scale-up is relatively easy, from a few MWth to 100 MWth. An inert material bed with particle size of between 0.05 and 0.5 mm is suspended as the oxidant agent is blown upwards through it with velocity of 5–10 m/s (McKendry, 2002). Feed particle size must not exceed 100 mm, entering the gasifier from the side, it is suspended and combusts to provide heat or reacts to form syngas. The mixture of syngas and particles are separated using a cyclone, with material returned to the base of the gasifier. Particles pass repeatedly through the circulation loop, the residence time for each circuit is only a few seconds. The

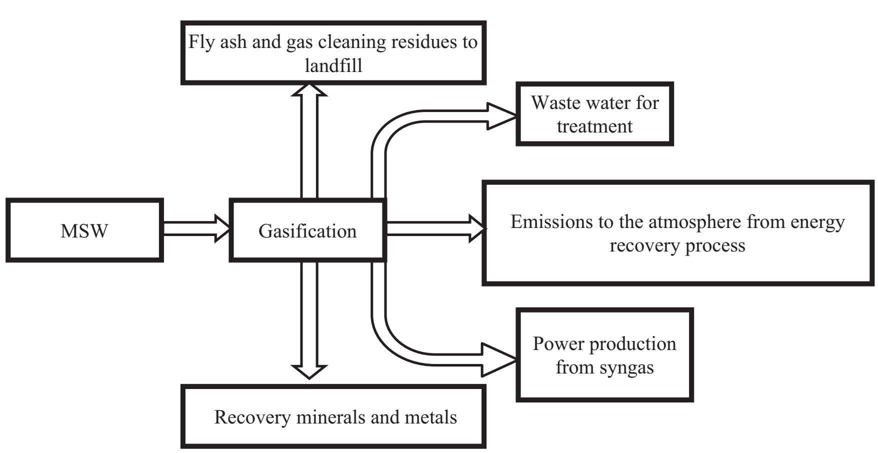

Fig. 5. Schematic representation of gasification inputs and outputs.

operating temperatures rage is 900–1000 °C to avoid ash melting and also can be pressurised (Bridgwater, 1995).

Dual fluidized bed gasifiers have two chambers; a gasifier and a combustor. Feed enters the gasification chamber and is converted to nitrogen-free syngas and char using steam. The char is burned in the combustion chamber, heating the accompanying bed of particles; the hot bed material is then fed back into the gasification chamber providing the indirect reaction heat. The cyclone removes the syngas from the mixture. The operating temperature is below 900 °C to avoid the ash melting and sticking to the wall of the gasifier. It can be pressurised (Basu, 2010).

Entrained flow gasifiers have an inconvenience in the operating process, since the waste particle size must be inferior to 1 mm, which means that feed has to be pre-treated to meet this specification, usually by grinding. To this fine fuel, water is added to form a slurry that is fed to the gasifier with pressurized oxygen and /or steam. The turbulent flame at the top of the gasifier burns some of the slurry, providing large quantities of heat at high temperature (1200–1500 °C). With this range of temperatures, ash melting will occur and eventually stick to the wall of the gasifier. Very short time residence in the range of a few seconds (Basu, 2010).

Plasma gasifiers do not have the need to pre-treat or downsize the MSW. The feed is dropped into the gasifier, coming into contact with electrically generated plasma, usually at atmospheric pressure. The operating temperatures are very high 1500–5000 °C; this means that heat exchange phenomenon is dominated by radiation. The organic matter is converted into syngas of very high quality, and inorganic matter is vitrified into inert slag. Note that plasma gasification uses plasma torches. It is also possible to use plasma arcs in a subsequent process step for syngas clean-up. Recent studies demonstrate that plasma gasification has very good potential in the treatment of MSW. The combination of high-temperature agent gasification and plasma melting has led to a new MSW disposal technology; named Plasma-Gasification-Melting (Qinglin et al., 2012).

3. Results

Fig. 6 shows the development of MSW generation reported in Portugal for the last six years reported compared with the PERSU II targets.

After 2007, production increased from 2008 to 2011, which is attributed to methodological changes arising from the use of the Map Records of Urban Waste in terms of recording and processing of data. In this context, from 2008 urban waste was defined by Chapters 15 and 20 of the European Waste Catalogue established by Commission Decision 2000/532/EC and transposed to the National legislation by the Ordinance n° 209/2004 of 3 March.

Based on a strategy of reduction of annual growth during the period of implementation of the plan 2007–2016, for 2010 an increase in production over 2009 was recommended, not exceeding 0.60% (MAOTDR, 2007). However, the actual data for 2010 indicate a total production of 5467 t of municipal waste, which corresponds to a growth of 1.18%, over the previous year. However, in 2011 the production was effectively reduced and was close to the target, which offers a good prospect for coming years. However, this decrease in MSW production is mainly attributed to the reduction of consumption due to the economic crisis the country is facing, below the PERSU II target in 2012.

The average production in the period 2007–2012 was 5175 kton/year, which is around 488 kg per capita per year considering an average population of 10.6 million. Considering the asymmetry in the population density in mainland Portugal, Fig. 7 shows the discrepancy of municipal waste production in each region of the country.

The North, Lisbon and the Tejo Valley regions accounted for 70% of MSW production in mainland Portugal in 2011. These results are not surprising because these regions have the densest populations of the country, as can be seen in Table 1. This is also the main reason for the energy recovery centres being located in these two regions.

Fig. 8 shows the waste treatment plan established for the period 2005–2016, which include 2005 as baseline. The moderate scenario goals for 2009, 2011 and 2016 were adopted.

In Fig. 8 a slight reduction in the percentage of MSW deposit in landfills is observed. However, it is very far from the PERSU II target for 2009, with double the percentage in 2011. This slow evolution of landfilled MSW shows that meeting the PERSU II target for 2016 will be a difficult task.

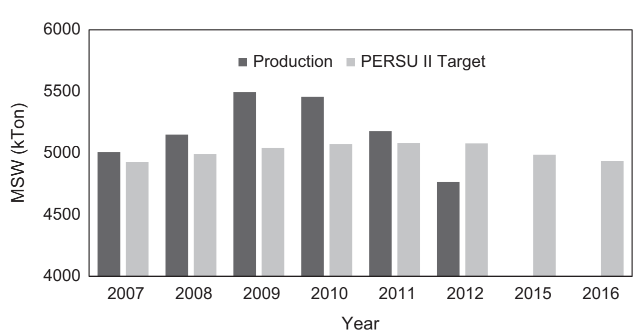

Fig. 6. Comparison of the MSW production in Portugal with PERSU II targets (APA, 2012).

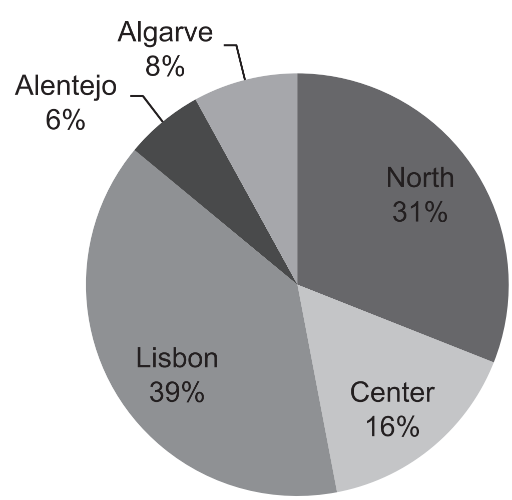

Fig. 7. Municipal waste production in mainland Portugal by region in 2011 (APA, 2012).

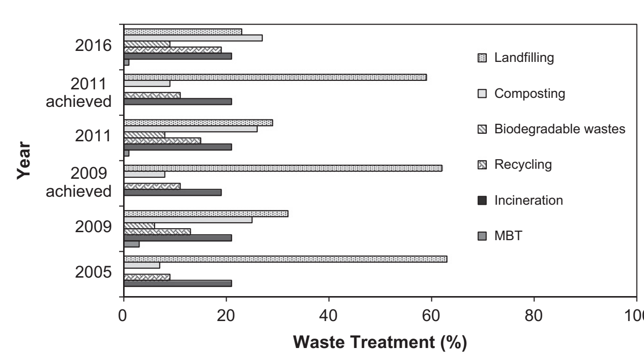

Fig. 8. Comparison of the 2009 and 2011 MSW treatments in Portugal with PERSU II targets (MAMAOT, 2012).

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002

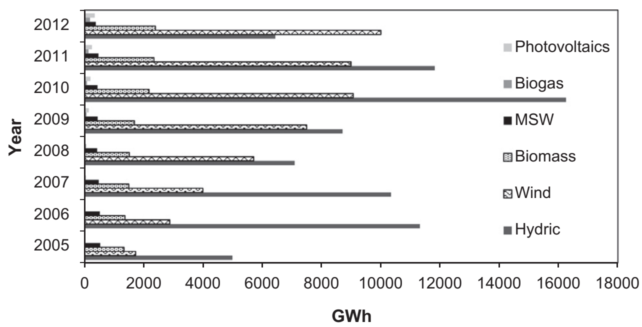

Fig. 9. Historical evolution of power produced from renewables in Portugal (DGEG, 2013).

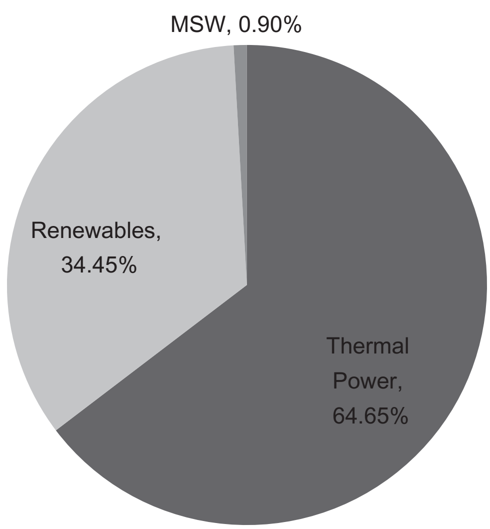

Fig. 10. Average representation of the MSW power production in the Portuguese power system.

Recycling is increasing slowly but is yet below the PERSU II target for 2009 and 2011. The biodegradable wastes are not shown due to the fact that they are produced in MBT units or from selective collection and included in the composting treatment (APA, 2012). Nevertheless, composting is far from the PERSU II targets.

Incineration has been attaining the PERSU II targets, which means that the PERSU II 2016 targets will be achieved through a reduction in the landfilled MSW that should be accomplished by increased recycling, composting, biodegradable wastes and in mechanical biological treatment. Ten new facilities for organic recovery were under construction in 2010 (most of them MBT facilities making use of anaerobic digestion) and another five facilities were projected for the organic recovery of MSW (APA, 2012). These new facilities can be expected to significantly change the waste management situation, but the way the treated MSW amounts are reported is crucial for properly accounting for this change (ETC/SCP, 2013).

In the period under PERSU II, power production from renewables in Portugal is shown in Fig. 9. The average share of power production based on MSW was around 3%. This percentage is very low since the country has a strong stake in hydro and wind power.

In order to frame MSW power production in the national energy system, the average percentage for the years 2005–2012 is shown in Fig. 10.

It appears that the representativeness of power production based on MSW in Portugal is very low, not reaching 1%. However, as shown in Table 1 the potential is much higher. Therefore, MSW power production could easily double its share of the national power system.

4. Discussion

Portugal is facing multiple problems with MSW management and is attempting to tackle them by passing legislation in order to improve the performance of waste management systems. The country has made substantial progress in the waste domain since the end of the last century when depositing in open dumps was the dominant treatment method.

The drivers behind the developments in MSW include national legislation, which predominantly transpose EU Directives, and the National Waste Management Plans (PERSU). There have been two PERSUs in Portugal: PERSU I was ratified in 1997 and covered the period until 2006, when PERSU II came into force, which targeted the period 2007–2016.

PERSU I set both quantitative and qualitative targets for Portugal's MSW management system following developments at the EU level in parallel. The main objective of PERSU I was to eliminate open dumps and divert waste to recycling, incineration and composting according to specific quantified targets. This was a difficult task, as in 2001 more than 340 open dumps were yet to be closed (Magrinho et al., 2006). Despite the plan's success in eradicating open dumps, most of the set targets were not achieved (Ribeiro et al., 2011). Therefore, by taking into account the need to modernise the MSW system, PERSU II was ratified in 2006.

The legal framework governing waste management has been consolidated over the last few years with systems for managing certain specific flows and placing the onus on producers to pursue targets for prevention, separate collection, recycling and other forms of recovery. Besides the general framework such as PERSU, there are various other decrees regulating specific waste streams or treatment options.

The average level of waste generation in Portugal is comparable to other EU countries (514 kg/cap in 2010). Waste management is currently dominated by landfilling, but Portugal has invested in many other treatment options including incineration, composting and MBT technology, which will be fundamental for achieving the PERSUU II targets.

The lesson learned from the PERSU I was that the positive result of closing open dumps was substituted by landfills, which also have environmental problems. Portugal was unable to make a large step from open dumps to separate collection, recycling and other forms of recovery.

This scenario is likely to be repeated when it comes to waste to energy technologies with mass burn incineration being the most common method of thermal treatment for waste to energy facilities (Stantec, 2011). However, the landfill Directive of the European Union 1999/31/EC and the recent policy to tackle climate change and resource conservation, such as the deliberations at Copenhagen in 2009, encourage the development of renewable energy and landfill diversion technology, thereby providing gasification technology development with renewed support.

There are only two energy recovery centres associated with MSW management system as shown in Table 1. Considering the dimension of the existing incineration plants, it is possible to create at least two more in Resinorte and Ersuc, with similar dimension to the Lipor energy recovery plant of 25 MW. However, considering that the PERSU II target for incineration is achieved with two incineration power plants (Valorsul and Lipor), this target should be increased.

Gasification could be proposed as a viable alternative solution for waste treatment with energy recovery. It still faces some technical and economic challenges, mainly related to the highly heterogeneous nature of the MSW and the relatively limited number of these plants worldwide that have continuous operating experience under commercial conditions (Umberto, 2012). In the working environment of MSW management with its uncompromising demand for reasonable cost, high reliability and

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002

operational flexibility, it could be premature to indicate gasification as the thermal processing strategy of the future or even as a strong competitor for combustion systems.

The environmental performance of gasification technology is one of its greatest strengths, so it is often considered as a comprehensive response to the increasingly restrictive regulations applied around the world. Independently verified emissions tests indicate that gasification is able to meet existing emissions limits and can have a great effect on the reduction of landfill disposal option. Economic aspects are probably the deterring factor for relevant market penetration, since gasification-based plants tend to have higher ranges of operating and capital costs, on the order of about 10% more than conventional combustion-based plants, mainly as a consequence of the ash melting system and the added complexity of the technology (Umberto, 2012).

The greatest technical challenges to be overcome for a wider market penetration of commercial advanced gasification technologies appear to be improved and cheaper syngas cleaning, able to conveniently meet defined specifications and to obtain higher power conversion efficiencies. The next few years will show whether the results of active R&D programs worldwide along with performance data and know-how from several commercial waste gasifiers in operation will allow the gasification process to be considered as a strong competitor of conventional moving grate or fluidized bed combustion systems.

This problem can be tackled with the recent technology of waste gasification by thermal plasma. The plasma treatment allows a significant purification of gas by limiting the production of tars and producing a synthesis gas enriched in hydrogen (water-gas shift reaction). Plasma methods have also the advantages of being able to operate at high temperature and to be retrofitted to existing installations (Frédéric Fabry et al., 2013). Such a temperature in plasmas can allow synthesizing or degrading chemical species in some conditions which are unreachable by conventional combustion and can greatly accelerate chemical reactions. The reactive species produced by the plasma, such as atomic oxygen and hydrogen or hydroxyl radicals, is an additional advantage for the use of plasma and strongly enhance the degradation of tars with greater efficiency than conventional processes (Frédéric Fabry et al., 2013).

Concerning the development and the operation of plasma technologies in the energy market, at present the technical feasibility and economic viability of plasma vitrification technologies have been demonstrated for a large range of hazardous wastes but this is not the case of plasma gasification technologies for the disposal of MSW on an industrial scale.

5. Conclusions and policy implications

The influence of MSW strategic plans and legislation on the waste management systems and infrastructure facilities in Portugal was assessed along with the technologies associated with MSW treatment. Despite all these strategic plans most of the MSW in Portugal are sent to landfill. Portugal is still 20% above the landfill disposal average of the EU-27. In Portugal, until 2020 it is expected that the landfill decrease will be higher than the EU average with a slight increase in incineration due to potential new incineration plants.

The launch of the second national waste management plan (PERSU II) in 2006 aimed at tackling the inefficiencies of the previous national plan and aligning the country with EU standards and targets. The new MBT plants under construction in 2010 can be expected to have a significant effect on the development of the entire MSW management system in the future. However, Portugal needs to intensify its efforts for meeting the final two targets of the Landfill Directive 1999/31/EC. Portugal is rescheduling and readjusting the management of biodegradable municipal waste in line with the landfill diversion targets for 2020. It is expected that this effort, together with the full operation of all the facilities projected for biodegradable municipal waste recovery, will reverse the present situation and contribute to compliance with its landfill diversion target. Portugal will need to make an exceptional effort in order to meet the 50% recycling target of the Waste Framework Directive 2008/98/EC by 2020.

At the technological level, incineration continues to be the most common method of thermal treatment for waste-to-energy facilities. However, with the enhancement of environmental restrictions and the development of gasification technology, gasification presents an increasingly efficient and viable alternative to incineration. Gasification is a waste-to-energy conversion scheme that offers a most attractive solution to both waste disposal and energy problems. However, gasification still has some economic and technical challenges, concerning the nature of the solid waste residues and is heterogeneity. The greatest strength of gasification is the environmental performance, since emission tests indicate that gasification meets the existing limits and it can also have an important role in the reduction of landfill disposal. However, considering that the PERSU II target for incineration was already achieved with the two existing incineration power plants, this target should be increased in order to give imputus to market penetration. Nevertheless, the economic aspect is the crucial factor to market penetration, since the capital cost of gasification tends to be higher than the usual incineration process.

This is a growing market and the efficiency of waste gasification by plasma appears to be validated, but the economic viability of this technology must be proven before being accepted by the industry. Presently, the strong expansion of numerous plasma gasification plants around the world indicates a trend, and in the future plasma gasification is very likely to play a significant role in the field of renewable energy.

Acknowledgments

This project is been supervised by Prof. Abel Rouboa, Prof. Armando Soares, Prof. Eliseu Monteiro and Dr. Valter Silva within the funded national project PTDC/AAC-AMB/103119/2008 and the financial support of LIPOR (Serviço Intermunicipalizado de Gestão de Resíduos do Grande Porto).

References

APA, 2010. Characterization of municipal solid waste in mainland Portugal in 2009. Environmental Protection Agency of Portugal. (Available on)⟨http://www.apambiente.pt/politicasambiente/Residuos/gestaoresiduos/RU/Documents/Relatorio_RU_2009.pdf⟩.
APA, 2012. Portugal state of the environment report 2012. Charts and Figures (Available on)⟨http://sniamb.apambiente.pt/docs/REA/Portugal_REA2012_Charts&Figures.pdf⟩.
Johari, Anwar, Isa Ahmed, Saeed, Hashim, Haslenda, Alkali, Habib, Ramli, Mat, 2012. Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. Renew. Sustain. Energy Rev. 16, 2907–2912.
Basu, P., 2010. Biomass Gasification and Pyrolysis: Practical Design and Theory. Elsevier, Oxford.
Belevi, H., Moench, H., 2000. Factors determining the element behaviour in municipal solid waste incinerators. Environ. Sci. Technol. 34 (12), 2501–2506.
Biniecka, M., Campana, P., Tarola, A.M., 2005. Thermo-valorisation in integrated waste management. Microchem. J. 79, 319–324.
Bridgwater, A.V., 1995. The technical and economic feasibility of biomass gasification for power generation. Fuel 74 (5), 631–653.
Higman, Christopher, Burgt, Marteen van der, 2003. Gasification. Elsevier, New York.
COM, 2000. Commission decision 2000/532/EC of 3 May 2000 on the European list of wastes. Off. J. Eur. Communities, L 226, 3–24.
David, L., Marion, C., Heijo, S., Jeremy, W.F.M., Morton, A.B., 2012. A review of approaches for the long-term management of municipal solid waste landfills. Waste Manag 32, 498–512.

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002

Decree-Law n° 366-A/97. Diário da República – I Série – A, n° 293, de 20 de Dezembro de 1997, 498–502.
Decree-Law° 178/2006. Diário da República, 1ª série–N.° 171–5 de Setembro de 2006, 6526-6545.
Decree-Law° 73/2011. Diário da República, 1.ª série – N.° 116 – 17 de Junho de 2011, 3251-3300.
DGEG, 2013. Renováveis – Estatísticas Rápidas. N° 105. Available on: 〈http://www.dgeg.pt〉.
Ecke, H., Sakanakura, H., Matsuto, T., Tanaka, N., Lagerkvist, A., 2001. Effect of electric arc vitrification of bottom ash on the mobility and fate of metals. Environ. Sci. Technol. 35 (7), 1531–1536.
ETC/SCP, 2013. Municipal waste management in Portugal, ETC/SCP Working paper, Copenhagen (Available on).
European Commission, 2002. Economic analysis of options for managing biodegradable municipal waste. Eunomia Final Report. Available on: 〈http://ec.europa.eu/environment/waste/compost/pubs.htm〉.
European Commission, 1975. European Council Directive 75/442/EEC of 15 July 1975 on waste. Off. J. L 194, 39–41.
European Commission, 1994. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. Off. J. L 365, 10–23.
European Commission, 1999. European Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Off. J. L 282, 1–19.
European Commission, 2000. Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. Off. J. L 332, 91–111.
European Commission, 2004. Directive 2004/12/EC of the European Parliament and of the Council of 11 February 2004 amending Directive 94/62/EC on packaging and packaging waste – Statement by the Council, the Commission and the European Parliament. Off. J. L 47, 26–31.
European Commission, 2006. Directive 2006/12/EC of the European Parliament and of the Council of 19 November 2086 on waste and repealing certain Directives. Off. J. L 312, 3–30.
European Commission, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 15 April 2006 on waste. Off. J. L 114, 9–21.
Eurostat, 2010. Europe in Figures – Eurostat Yearbook. Eurostat Statistical Books, Brussels, Belgium p. 2010.
E4tech, 2009. Review of Technologies for Gasification of Biomass and Wastes. NNFCC project 98/008. Available on 〈www.nnfcc.co.uk〉.
Frédéric Fabry, Christophe Rehmet, Rohani, Vandad, Fulcheri, Laurent, 2013. Waste gasification by thermal plasma: a review. Waste Biomass Valor 4, 421–439.
Hartenstein, Hans-Ulrich, Horvay, Marc, 1996. Overview of municipal waste incineration industry in west Europe (based on the German experience). J. Hazard Mater. 47, 19–30.
Heron, K., Soren, D., 2007. 100 Years of Waste Incineration in Denmark. Ramboll Group, Denmark.
Jung, C.H., Matsuto, T., Tanaka, N., Okada, T., 2004. Metal distribution in incineration residues of municipal solid waste. Waste Manag 24 (4), 381–391.
Kantarelis, Kantarelis E., Zabaniotou, A., 2009. Valorization of cotton stalks by fast pyrolysis and fixed bed air gasification for syngas production as precursor of second generation biofuels and sustainable agriculture. Bioresource Technol. 100, 942–947.
Magrinho, A., Didelet, F., Semião, V., 2006. Municipal solid waste disposal in Portugal. Waste Manag 26, 1477–1489.
MAMAOT, 2012. PERSU II - Plano Estratégico para os Resíduos Sólidos Urbanos 2007–2016. Relatório de Acompanhamento 2010. Ministério da Agricultura, do Mar, do Ambiente e do Ordenamento do Território. Available on: 〈www.apambiente.pt/_cms/view/page_doc.〉. php?id=635.
MAOTDR, 2007. Plano Estratégico dos Resíduos Sólidos Urbanos 2007-2016. Ministério do Ambiente do ordenamento do território e do desenvolvimento regional. Available on: 〈www.maotdr.gov.pt/Admin/Files/Documents/PERSU.pdf〉.
McKay, Gordon, 2002. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review. Chem. Eng. J. 86, 343–368.
McKendry, P., 2002. Energy production from biomass (part 3): gasification technologies. Bioresource Technol. 83, 55–63.
Monteiro, E., Mantha, V., Rouboa, A., 2010. Prospective application of farm cattle manure for bioenergy production in Portugal. Renew. Energ. 36 (2), 627–631.
Ordenance no 15/96. Diário da República – I Série-B - N.° 19 — de 23 de Janeiro de 1996, 128–129.
Qinglin, Z., Liran, D., Dikla, F., Weihong, Y., Wlodzmierz, B., 2012. Gasification of municipal solid waste in the Plasma Gasification Melting process. Appl. Energy 90, 106–112.
Ribeiro, A., Castro, F., Macedo, M., Carvalho, J., 2011. Waste Management in Portugal and Europe – An overview of the past, present and future. Wastes: Solution, Treatments and Opportunities. 1st Conference September 12th – 14th, 2011.
Smith, A., Brown, K., Ogilvie, S., Rushton, K., Bales, J., 2001. Waste management option and climate change, European Communities. Final report to the European Commission. DG Environment, Luxembourg.
Stantec, 2011. Waste to Energy: A Technical Review of Municipal Solid Waste Thermal Treatment Practices. Stantec Consulting Ltd, Canada (Available from).
Umberto, A., 2012. Process and technological aspects of municipal solid waste gasification: a review. Waste Manag 32, 625–639.
Weber, LWD, Greim, H., 1997. The toxicology of brominated and mixed-halogenated dibenzo-p-dioxins and dibenzofurans: an overview. J. Toxicol. Environ. Health 50, 195–215.
World Bank, 2000. Municipal Solid Waste Incineration-Decision Maker's Guide. Washington, D.C.

Please cite this article as: Teixeira, S., et al., Prospective application of municipal solid wastes for energy production in Portugal. Energy Policy (2014), http://dx.doi.org/10.1016/j.enpol.2014.04.002