Potential and cost of electricity generation from human and animal waste in Spain

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A R T I C L E   I N F O

Article history:
Received 27 May 2009
Accepted 22 July 2009
Available online 6 September 2009

Keywords:
Biogas
Municipal solid waste
Sewage sludge
Livestock manure
Renewable energy
GIS

A B S T R A C T

The energy contents of human and animal waste generated in Spain is estimated, as is the electricity that could be potentially generated from such waste. The waste considered is municipal solid waste, sewage sludge and livestock manure; several energy-recovery options are analyzed for the first one, viz the collection of landfill gas, incineration and anaerobic digestion. To estimate the potential, we use georeferenced statistical human and animal population data disaggregated to the county level. This level of disaggregation allows the implementation of a cost model for the transformation of the waste into electricity, using a variety of technologies. The model considers the cost of transporting the waste to the transformation plant, and takes into account the economies of scale afforded by larger plants for the combined treatment of the waste in the county. The result is a generation-cost curve, which sorts by increasing costs the generation potential in the whole of the territory. The overall limits, in terms of primary energy and without considering alternative uses for the waste are between 725 and 4438 ktoe/y (depending on the energy-recovery method) for municipal solid waste; 142 ktoe/y for sewage sludge; and 1794 ktoe/y for livestock manure. The cost of the electricity generated depends greatly on the type of residue and the technology used for the transformation. Thus, the most economical option is the incineration of municipal solid waste, with an entry cost of around 4 c/kWh. The generation entry-costs from livestock manure and sewage sludge are on the other hand in excess of 8 c/kWh.

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1. Introduction

Sustainable development policies often involve the appropriate processing of waste such as municipal solid waste (MSW), sewage sludge and livestock manure. In Europe, and elsewhere, policies are encouraging the reduction and recycling of waste, and also its energy use. Thus, Council Directive 1991/31/EC imposes a reduction in the total amount of biodegradable waste going to landfill in the EU Member States; Directive 86/278/EC encourages the use of sewage sludge in agriculture (after appropriate treatment and provided that its addition to the soil is harmless); Directive 1991/676/EC addresses the reduction of the release of nitrates from agricultural activities to surface and ground waters, fostering the sustainable recycling of animal manure. Furthermore, the Council of European Union has approved recently an energy plan, which includes an objective of 20% of renewable energy in the final energy consumption in Europe by 2020. The use of the energy in human and animal residues can contribute to this challenging target; and especially so in Spain, which has the fifth largest population of the EU Member States (46 million inhabitants) and the third largest livestock sector of the EU countries: 6.4 million bovine heads (or 7% of EU total), 22.7 million sheep (19%), 2.9 million goats (22%), 24.8 million pigs (15%), 158.2 million poultry (15%), 2.4 million rabbits and 292,000 horses. The aim of the present work is to assess the potential for electricity generation from these residues, in terms of both the amount of energy that can be generated and the generation-costs.

Following its widespread definition, MSW is considered in this work to include all kind of residues generated from homes, businesses, and the cleaning of public places such as streets, parks, beaches and other recreational areas. There are a number of technological options for the energy use of MSW, including the recovery of landfill gas, incineration, gasification, production of H2, pyrolysis and anaerobic digestion of the organic fraction. In this study, we will consider the potential of generating electricity from landfill gas, incineration and anaerobic digestion. Landfill gas involves the extraction of the biogas spontaneously generated from the disposal of MSW in landfills, and its use for electricity generation using (alternatively) reciprocating internal combustion engines, gas turbines, boilers and steam turbines, microturbines or fuel cells [1,2]. The incineration of MSW, usually in grate boilers, uses the released heat to generate electricity in a steam turbine. The
anaerobic digestion of the organic fraction of MSW reproduces the natural process of degradation of the organic matter in the landfill, but using reactors under controlled operating conditions. The biogas produced can be used to generate electricity with the same technologies as for landfill gas; compost is also often a by-product.

Sewage sludge is the residue generated during the primary, secondary and tertiary treatment processes of waste water. Sludge is usually liquid or semisolid, the solids concentration being normally in the range 0.25–12% [3], depending on the methods for effluent treatment employed. Although there are other residues generated in the treatment processes of waste water, such as grit and screening, sewage sludge is by far the largest in volume. There are different options for the final use of sewage sludge, the most employed being disposal in landfills, generation of compost and incineration [4]. Prior to its final use, sewage sludge is processed mainly in two stages: biological stabilization and dewatering. The biological stabilization can be achieved through several processes: anaerobic digestion, aerobic digestion or lime addition [3]. In this work, anaerobic digestion of sewage sludge is considered for its final energy use.

Livestock manure refers in the context of this work to stock-raising animal droppings. If uncontrolled, these residues can lead to air and water pollution, specially in zones with a high density of farming systems. For this reason, their handling is a matter of great concern from an environmental point of view. Due to their high moisture, anaerobic digestion is the more common option for the energy use of livestock manure, and it is the option considered in this work.

There are a number of published studies on the energy potential of residues. Most of them are concerned with bioenergy potentials in general, and, report the energy potential of residues since they are considered a type of biomass. Examples of this kind of studies are: Hoogwijk [5] and Fischer and Schrattenholzer [6], who estimate the energy potential of animal and organic residues worldwide; Siemons et al. [7] and Wiesenthal et al. [8], who reported energy potentials of residues for EU countries; and Bauen et al. [9] who presented energy potentials of livestock manure for OECD countries. There are also some studies on the energy potential of residues specifically. Thus, Marxsen [10] presented results for the worldwide generation of MSW, sewage sludge, animal excrement, industrial waste and other residues; Brodersen et al. [11] carried out a similar work for EU countries; Minowa et al. [12] estimated the energy potential of organic residues in Japan; Fujino et al. [13] made a similar study for livestock manure in Japan; Jensen and Jepsen [4] estimated sewage sludge production in Denmark; and Batzias et al. [14] evaluated livestock manure for biogas production in Greece. In general, the methodology used in these studies is straightforward. Using statistical data on the production of residues, availability factors for the residues, and assuming an energy content for them, the energy potential is calculated. Batzias et al. [14] implement this methodology in a geographic information system, obtaining geo-referenced results. None of these studies, however, presents an economic analysis leading to estimates of the cost of the electric energy produced.

On the other hand, there are studies which present a detailed economic and environmental analysis of the several options for the energy use of residues (for instance, Dornburg and Faaij [15], Lundin et al. [16], Murphy et al. [17] and Murphy and McKeogh [18]); aim of such studies is not the assessment of waste resources, but the analysis of different waste management routes from an economic and environmental point of view.

In this work a methodology for energy and economic potential of MSW, sewage sludge and livestock manure is presented. This methodology is integrated into a geographic information system, leading to geo-referenced results. The methodology used for the economic study assesses the generation-cost using a cost-potential curve; different options for the transformation of the residues into electricity are considered. The methodology is described in detail in the next sections.

2. Method for estimating the potential

In this section the methodology used for the calculation of the electric energy potential of MSW, sewage sludge and livestock manure is presented. The focus is on the calculations carried out for sewage sludge, livestock manure and municipal waste of all kind. The calculation methodology is integrated into a geographic information system, obtaining geo-referenced results.
manure is described. The potential is calculated locally, at the county (Spanish: comarca) level, using geo-referenced data, and it is then aggregated nationally. There are a total of 324 counties in Spain, varying in size from 251 to 5482 km².

2.1. Municipal solid waste

The electric energy potential of MSW is calculated considering three alternatives for its transformation: the recovery of landfill gas, incineration and anaerobic digestion.

The first step for the estimation of the MSW potential is the calculation of the quantity and composition of MSW. These are parameters that depend on cultural and socioeconomic factors [19–21]. For example, the organic content of MSW is lower in rural areas, as they are commonly used for animal feeding; the type of waste generated differs from residential to service-sector areas; and the fraction of packaging materials in the waste is larger in developed countries. Other factors as such weather or the season (e.g. in tourist locations) should also be taken into account. Nevertheless, the most common approach is to use an annually-averaged generation rate and composition, which is calculated, with a certain spatial granularity, using statistical data. In this study, these data have been obtained from the Spanish Ministry of the Environment [22]. Table 1 shows the generation of MSW per capita, disaggregated by autonomous regions; and Table 1 shows the average composition of MSW in Spain in 2005.

2.1.1. Landfill gas

The potential of landfill gas is defined as the electricity that would be produced from it if all the MSW were disposed in landfills; the national potential is calculated using county level data as:

\[ \pi_{FG} = \sum \frac{P_r}{P}\cdot R_{AR}(c)\cdot MQ\cdot \eta_e \]  

(1)

where \( P_r \) is the resident population in county \( c \) [23], \( R_{AR}(c) \) is the annual residue generation (Table 1) per capita [22] in the autonomous region where county \( c \) is, \( M \) is the methane generation rate in the landfill per tonne of MSW (Nm³ t⁻¹) and \( Q \) is the lower heating value of methane (37.2 MJ Nm⁻³). The methane generation rate in landfills depends on a number of factors: composition of MSW, ambient temperature, rainfall, presence of inhibitors, nutrients, the design of the landfill or the crushing of MSW prior to its disposal in the landfill. This has resulted in different generation rates being reported in the literature, ranging from 67.5 to 122 Nm³ t⁻¹ MSW [19,29–32]. In this study, a value of 71 Nm³ t⁻¹ MSW has been adopted. The value of \( \eta_e \) has been taken as 0.26 [18]; this value is lower than the efficiency reported for the reciprocating internal combustion engine (ICE) since it is not net of the electric energy required for internal consumption by the plant.

2.1.2. Incineration

The potential for electricity generation via the incineration of all the MSW generated in Spain is calculated from county data as:

\[ \pi_{INC} = \sum \frac{P_r}{P}\cdot R_{AR}(c)\cdot MQ_{MSW}\cdot \eta_e \]  

(2)

where \( Q_{MSW} \) is the lower heating value of the MSW and \( \eta_e \) the efficiency of the transformation into electric energy. \( Q_{MSW} \) is calculated using the average composition of the MSW (shown in Table 2) and the lower heating value for each type of residue [27], viz: 2.72 MJ kg⁻¹ for organic matter, 10.05 MJ kg⁻¹ for paper, 13.58 MJ kg⁻¹ for wood, 14.35 MJ kg⁻¹ for textiles, 35.22 MJ kg⁻¹ for plastics and 0 MJ kg⁻¹ for glass, metals and others. The resulting value of \( Q_{MSW} \) is 7.98 MJ kg⁻¹. Finally, a value of \( \eta_e = 0.29 \), corresponding to grate incineration, is assumed [28].

2.1.3. Anaerobic digestion

The potential for electricity production for the anaerobic digestion of the whole organic fraction of MSW (OFMSW) generated in Spain is estimated as:

\[ \pi_{OFMSW} = \sum \frac{P_r}{P}\cdot R_{AR}(c)\cdot MQ\cdot \eta_e \]  

(3)

where \( f \) is the fraction of organic matter in MSW, 0.489 [22] and \( M_{OFMSW} \) is the methane generation rate per tonne of OFMSW (Nm³ t⁻¹). Although the anaerobic digestion is carried out under controlled operating conditions, different values for the amount of methane generated from OFMSW are reported in the literature, ranging from 67.5 to 122 Nm³ t⁻¹ OFMSW [19,29–32]. In this study, a value of 71 Nm³ t⁻¹ OFMSW [26] has been adopted. The value of \( \eta_e \) has been taken as 0.26 [18]; this value is lower than the efficiency reported for the reciprocating internal combustion engine (ICE) since it is not net of the electric energy required for internal consumption by the plant.

2.2. Sewage sludge

The electricity generation potential of sewage sludge (SWSL) is the electricity that would be produced with the biogas obtained from the anaerobic digestion of all the sewage sludge generated in Spain; it is calculated from county data as:

\[ \pi_{SWSL} = \sum \frac{P_r}{P}\cdot R_{SWSL}\cdot SM\cdot SWSL\cdot \eta_e \]  

(4)

where \( R_{SWSL} \) is the annual per capita generation rate of dry sewage sludge kg capita⁻¹ y⁻¹, \( S \) is the fraction of volatile solids in the dry sewage sludge kg VS kg⁻¹ dry sewage sludge and \( SWSL \) is the methane generation rate per kilogram of volatile solids Nm³ kg⁻¹ VS. Several values for \( R_{SWSL} \) are reported in the literature [3,4,10,16,33,34], ranging from 20.00 to 32.85 kg capita⁻¹ y⁻¹. In this study, a value of 26.6 kg capita⁻¹ y⁻¹ is used. Values of \( S \) are reported in different references [33,35–39] as being between 0.49

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Table 1

<table>
<thead>
<tr>
<th>Autonomous region</th>
<th>t capita⁻¹ y⁻¹</th>
<th>Autonomous region</th>
<th>t capita⁻¹ y⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andalucia</td>
<td>0.543</td>
<td>Valencia</td>
<td>0.443</td>
</tr>
<tr>
<td>Aragon</td>
<td>0.478</td>
<td>Extremadura</td>
<td>0.332</td>
</tr>
<tr>
<td>Asturias</td>
<td>0.496</td>
<td>Madrid</td>
<td>0.572</td>
</tr>
<tr>
<td>Baleares</td>
<td>0.737</td>
<td>Murcia</td>
<td>0.438</td>
</tr>
<tr>
<td>Canarias</td>
<td>0.587</td>
<td>Navarra</td>
<td>0.467</td>
</tr>
<tr>
<td>Cantabria</td>
<td>0.412</td>
<td>País Vasco</td>
<td>0.510</td>
</tr>
<tr>
<td>Castilla-La Mancha</td>
<td>0.408</td>
<td>La Rioja</td>
<td>0.510</td>
</tr>
<tr>
<td>Castilla-Leon</td>
<td>0.584</td>
<td>Ceuta</td>
<td>0.565</td>
</tr>
<tr>
<td>Cataluña</td>
<td>0.522</td>
<td>Melilla</td>
<td>0.624</td>
</tr>
<tr>
<td>Galicia</td>
<td>0.332</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>MSW composition</th>
<th>%</th>
<th>Q (MJ kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic matter</td>
<td>48.9</td>
<td>2.72</td>
</tr>
<tr>
<td>Paper</td>
<td>20.5</td>
<td>10.05</td>
</tr>
<tr>
<td>Wood</td>
<td>0.6</td>
<td>13.58</td>
</tr>
<tr>
<td>Textiles</td>
<td>3.7</td>
<td>14.35</td>
</tr>
<tr>
<td>Plastic</td>
<td>11.7</td>
<td>35.22</td>
</tr>
<tr>
<td>Glass</td>
<td>7.6</td>
<td>–</td>
</tr>
<tr>
<td>Metals</td>
<td>4.1</td>
<td>–</td>
</tr>
<tr>
<td>Others</td>
<td>2.9</td>
<td>–</td>
</tr>
</tbody>
</table>
and 0.72 kg VS kg\(^{-1}\) dry sewage sludge; a value of 0.49 kg VS kg\(^{-1}\) dry sewage sludge has been adopted. The value of \(M_{\text{MSW}}\) is 0.276 Nm\(^3\) kg\(^{-1}\) VS [40]. The value of \(\eta_e\) has been taken, as for the anaerobic digestion of OFMSW, as 0.26.

2.3. Livestock manure

The potential for the generation of electricity from livestock manure is calculated considering its transformation into biogas via anaerobic digestion. The first step for the calculation is the estimation of the number of heads of the several groups of stock-raising animals in Spain. The following groups have been considered: cattle, pigs, sheep, goats, horses, poultry and rabbits. Because of the variability found in residue generation rates and in contents of organic matter according to the sex and the age of cattle and pigs, appropriate subdivisions have been considered for this categories. Data for the number of heads of each livestock in the several regions of Spain have been obtained from refs. [41–43]. Next, the amount of excrements generated by each livestock type, and the rate per kilogram of dry solids \(N_{\text{c}}\) has been obtained from refs. [14] and [44], and considered separately for each residue feed. Thus, for MSW, this analysis are the same as the counties (comarcas) used above. In order to avoid excessively large units, a maximum plant size is considered. A generation-cost curve is constructed with the data for each county.

Table 3

<table>
<thead>
<tr>
<th>Livestock</th>
<th>R (kg head (^{-1}) y(^{-1}))</th>
<th>(\eta^a)</th>
<th>S (kg dry solids kg(^{-1}) residue)</th>
<th>M (Nm(^3) kg(^{-1}) dry solids)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy</td>
<td>23,020</td>
<td>0.45</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>Other cattle</td>
<td>13,870</td>
<td>0.45</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>Bull &gt;24 months</td>
<td>23,020</td>
<td>0.45</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>Cattle 12–24 months</td>
<td>8030</td>
<td>0.45</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>Cattle &lt;12 months</td>
<td>1277</td>
<td>0.45</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>Sow</td>
<td>4380</td>
<td>0.45</td>
<td>0.08</td>
<td>0.29</td>
</tr>
<tr>
<td>Other pigs</td>
<td>1870</td>
<td>0.80</td>
<td>0.07</td>
<td>0.29</td>
</tr>
<tr>
<td>Piglet</td>
<td>486</td>
<td>0.80</td>
<td>0.08</td>
<td>0.29</td>
</tr>
<tr>
<td>Sheep</td>
<td>394</td>
<td>0.35</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>Goat</td>
<td>958</td>
<td>0.35</td>
<td>0.32</td>
<td>0.07</td>
</tr>
<tr>
<td>Horse</td>
<td>9125</td>
<td>0.10</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>Poultry</td>
<td>40</td>
<td>0.70</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>Rabbit</td>
<td>56</td>
<td>0.05</td>
<td>0.52</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Thus, the potential for electricity generation with the anaerobic digestion of the whole livestock manure generated in Spain is calculated, using county data, as:

\[
\pi_{\text{LVM}} = \sum_c \sum_a N_a^c R^a \eta^a S^a M^a Q \eta_e
\]  

(5)

where \(N_a^c\) is the headcount for livestock animal \(a\) in county \(c\) [41–43], \(R^a\) is its residue generation rate, \(\eta^a\) is the fraction of the residue that can be collected (depending, for instance, on the type of animal confinement), \(S^a\) is the fraction of dry solids in the residue \(kg\) dry solids \(kg^{-1}\) residue for animal \(a\) and \(M^a\) is the methane generation rate per kilogram of dry solids \(Nm^3\) kg\(^{-1}\) dry solids. The net efficiency of the conversion of biogas into electric energy, \(\eta_e\), has been taken as 0.26, after considering the plant use of electricity. Values for \(R^a\), \(\eta^a\), \(S^a\) and \(M^a\) have been obtained from refs. [14] and [44], and are shown in Table 3; the availability factor \(\eta^c\) considers aspects such as alternative uses for manure (such as fertilizer) and the collectability, which depends on the confinement of the animals (see ref. [14] for details).

3. Economic methodology

The social interest of the energy conversion of human and animal waste is not determined only by specific cost of the energy generated; for instance, the appropriate management of waste can contribute to considerable reductions in GHG emissions. Despite these powerful environmental reasons for waste management, an economic analysis of its energy potential allows the comparative study of alternative technologies, and an assessment of their competitiveness with other electricity generation technologies, whether renewable or otherwise.

Unlike some other renewable energy sources, such as solar or wind, the transformation of residues into energy is centralized in power generation units which are usually supplied from large residue-collection areas. This issue has been addressed in this study by dividing the area under study (the whole of Spain) into several regions; in each of them, one or several transformation units process all the residue generated in the region. The regions for this analysis are the same as the counties (comarcas) used above. In order to avoid excessively large units, a maximum plant size is considered. A generation-cost curve is constructed with the data for each county.

The technology used for the conversion into electrical energy is considered separately for each residue feed. Thus, for MSW, this economic analysis considers alternatively the use of landfill gas, incineration and anaerobic digestion; for sewage sludge and livestock manure only anaerobic digestion is considered. In the case of anaerobic digestion, the process includes the production of heat, a fraction of which is used for the process and the rest could be sold. Although there are installations for centralized anaerobic digestion in which several streams of wastes are treated jointly (for example, MSW and livestock manure), in the present analysis we consider the independent processing of each type of residue.

The unit cost of the electricity generated in a given county is calculated using the following equation:

\[
c_c \pi_c = aL_c + O_c - R^{hbp}_c
\]  

(6)

where \(c_c\) is the specific (unit) cost of the energy generated annually in the power plant installed in county \(c\); \(\pi_c\) is the energy generated.
annually in such plant; $a$ is the annuitization coefficient for the initial investment; $I_c$ is the capital cost of the installation; $O_c$ is the operation and maintenance cost and $R_{by}$ is the revenue obtained from the by-products, such as heat in the case of anaerobic digestion. Other possible sources of income from anaerobic digestion plants are the selling of composting or digestate. In this study, these are not considered. Transport costs are not included since it is assumed that these costs are borne by farmers (in the case of livestock manure) or inhabitants (in the case of MSW or sewage sludge) to eliminate their residues. The annuitization coefficient is given by $a = \frac{r}{1 - \frac{1}{(1 + r)^N}}$, where $r$ is the nominal discount rate (taken as 9%) and $N$ is the investment lifetime (taken...
as 20 years). Table 4 shows the economic parameters used for each technology.

Landfill gas investment costs include the biogas-collection system, the biogas-conversion system (reciprocating engine, gas turbine or steam turbine) and its ancillary equipment (pipelines, blowers and flares). For energy conversion, reciprocating engines have been assumed as they are the most commonly-employed systems in landfill gas installations. Investment costs for gas-collection systems are reported in refs. [1,46,47], and investment costs for reciprocating engines can be found in refs. [1,2,46–48]. An equation relating investment cost and installation size has been elaborated using this data, and it is shown in Table 4. The operation and maintenance cost used is that reported in ref. [2].

Investment costs for incineration include the combustion system (grate combustion in this study) and the steam cycle. Using data from refs. [18,28,49], the equation for investment cost versus installation size shown in Table 4 has been derived. Operating and maintenance costs are assumed to be 4% of the investment costs [28].

Anaerobic digestion is considered for the conversion into biogas of OFMSW, sewage sludge and livestock manure.

Investment costs for anaerobic digestion include the installation for the generation of biogas (e.g. sand trap, continuously stirred tank digestor, scrubbers and piping system) and the equipment for conversion of biogas into electrical energy. For the latter, a cogeneration facility in which electricity and heat are obtained is considered. Typical investment costs for this kind of installations are reported in refs. [18,28,50,51]. In this study, the investment cost suggested in ref. [50] has been selected. As operating and maintenance costs, 16% of investment cost, as it is reported in ref. [28], are taken. The electric efficiency is calculated considering the efficiency of an internal combustion engine and the plant use of electricity [52]. Heat efficiency is assumed to be 40% [17], and the thermal demand of the process is taken to be 30% of the generated heat; the balance is sold at the price indicated in Table 4.

4. Results and discussion

4.1. MSW

The energy potential obtained for MSW considering three alternative conversion technologies (landfill gas, incineration and anaerobic digestion) are summarized in Table 5. The electricity generation potential is 4.02 TWh/y for landfill gas, 15.02 TWh/y for incineration, and 2.20 TWh/y for anaerobic digestion of OFMSW. These values represent respectively 1.42, 5.32 and 0.78% of the net electric generation in Spain in 2006. In terms of primary energy, the landfill gas potential is 1045 ktoe/y (or 0.71% of the primary energy consumption in Spain in 2005), the incineration potential is 4438 ktoe/y (or 3.04%) and potential of anaerobic digestion of OFMSW is 752 ktoe/y (or 0.51%).
energy consumption in Spain in 2005. Fig. 2 shows the geographical

The aggregated potential (in terms of electrical energy) from all these residue sources ranges from 8.13 TWh/y (if anaerobic digestion for MSW is considered) to 20.95 TWh/y (if incineration is adopted for MSW). These potentials are equivalent to between 2.82 and 7.42% of the net electric generation in Spain in 2005. These potentials estimated in the present study are in line with the ones reported in other studies. Taking into account that the contribution of renewable electric energy in Spain in 2005 was 52 TWh [53], the waste electric potential is not negligible.

The entry cost of the electricity generated depends largely on the technology used for the recovery of the energy from waste. Thus, the entry cost of electricity from incineration and landfill gas is lower than the average cost of electricity in Spain in 2006, estimated at 0.083 €/kWh [54]; and the cost of electricity generation by means of anaerobic digestion (organic fraction of MSW, sewage sludge and livestock manure) is greater.

The overall electricity potential of livestock manure (considering anaerobic digestion and the transformation of the gas in internal combustion engines) is 5.44 TWh/y. This value is equivalent to 1.92% of the net electric generation in Spain in 2006 [53]. In terms of primary energy, the potential of livestock manure is 1794 ktoe/y (equivalent to 1.23% of the primary energy consumption in Spain in 2005).

Fig. 3 shows the geographical distribution of this potential. The spatial distribution in this case is different from the observed for MSW and sewage sludge, since livestock-raising regions in Spain usually have a low population density. Fig. 4 shows the generation-cost curve for livestock manure. The entry cost is about 0.09 €/kWh, similar to the entry cost for anaerobic digestion of OFMSW.

4.4. Comparison with other studies

Table 6 compares results from this work with those from other published studies. In general, the results obtained here are consistent with the potential reported by others, considering the diversity of approaches and data sources used. Siemons et al. [7] present results for years 2010 and 2020; for MSW residues in 2020, they consider a larger contribution of incineration to energy-recovery from MSW because of the application of Council Directive 1999/31/EC.

5. Conclusions

In this work a methodology for the evaluation of the energy potential of MSW, sewage sludge and livestock manure has been presented. The methodology is integrated in a geographic information system and the results are geo-referenced.

The aggregated potential (in terms of electrical energy) from all these residue sources ranges from 8.13 TWh/y (if anaerobic digestion for MSW is considered) to 20.95 TWh/y (if incineration is adopted for MSW). These potentials are equivalent to between 2.82 and 7.42% of the net electric generation in Spain in 2005. These potentials estimated in the present study are in line with the ones reported in other studies. Taking into account that the contribution of renewable electric energy in Spain in 2005 was 52 TWh [53], the waste electric potential is not negligible.

The entry cost of the electricity generated depends largely on the technology used for the recovery of the energy from waste. Thus, the entry cost of electricity from incineration and landfill gas is lower than the average cost of electricity in Spain in 2006, estimated at 0.083 €/kWh [54]; and the cost of electricity generation by means of anaerobic digestion (organic fraction of MSW, sewage sludge and livestock manure) is greater.

In the future, Council Directive 1999/31/EC will force European countries to reduce MSW going to landfill. Therefore, recycling, incineration and anaerobic digestion of OMSW should all have an important role in the management of MSW. From an economic point of view, incineration of MSW is the most advantageous option. However, since waste management options are often based on other criteria than purely economic ones (such as environmental or social), anaerobic digestion should not be discarded as a future option for energy use of MSW, although cost reductions would be necessary. Improvement of anaerobic digestion technologies, a better understanding of the involved processes and deployment

### Table 6

<table>
<thead>
<tr>
<th>Source</th>
<th>Landfill gas</th>
<th>Incineration</th>
<th>Organic fraction MSW</th>
<th>Sewage sludge</th>
<th>Livestock manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study (ktoe/y)</td>
<td>1045</td>
<td>4438</td>
<td>725</td>
<td>142</td>
<td>1794</td>
</tr>
<tr>
<td>Siemons et al. [7], 2010 (ktoe/y)</td>
<td>503</td>
<td>1751</td>
<td>–</td>
<td>187</td>
<td>1412</td>
</tr>
<tr>
<td>Siemons et al. [7], 2020 (ktoe/y)</td>
<td>205</td>
<td>3480</td>
<td>–</td>
<td>206</td>
<td>1560</td>
</tr>
<tr>
<td>Wiesenthal et al. [8] (ktoe/y)</td>
<td>1300</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1420</td>
</tr>
<tr>
<td>Brodersen et al. [11] (ktoe/y)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>229</td>
<td>–</td>
</tr>
<tr>
<td>Bauen et al. [9] (ktoe/y)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1404</td>
</tr>
</tbody>
</table>

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### 4.3. Livestock manure

The overall electricity potential of livestock manure (considering anaerobic digestion and the transformation of the gas in internal combustion engines) is 5.44 TWh/y. This value is equivalent to 1.92% of the net electric generation in Spain in 2006 [53]. In terms of primary energy, the potential of livestock manure is 1794 ktoe/y (equivalent to 1.23% of the primary energy consumption in Spain in 2005).

Fig. 3 shows the geographical distribution of this potential. The spatial distribution in this case is different from the observed for MSW and sewage sludge, since livestock-raising regions in Spain usually have a low population density. Fig. 4 shows the generation-cost curve for livestock manure. The entry cost is about 0.09 €/kWh, similar to the entry cost for anaerobic digestion of OFMSW.

### 4.4. Comparison with other studies

Table 6 compares results from this work with those from other published studies. In general, the results obtained here are consistent with the potential reported by others, considering the diversity of approaches and data sources used. Siemons et al. [7] present results for years 2010 and 2020; for MSW residues in 2020, they consider a larger contribution of incineration to energy-recovery from MSW because of the application of Council Directive 1999/31/EC.

### 5. Conclusions

In this work a methodology for the evaluation of the energy potential of MSW, sewage sludge and livestock manure has been presented. The methodology is integrated in a geographic information system and the results are geo-referenced.

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### 4.2. Sewage sludge

The energy potential of sewage sludge, considering its transformation via anaerobic digestion and internal combustion engines, is 0.49 TWh/y. This is equivalent to 0.15% of the net electric generation in Spain in 2006 [53]. In terms of primary energy, the sewage sludge potential is 142 ktoe/y, or 0.10% of the primary energy consumption in Spain in 2005. Fig. 2 shows the geographical distribution of the energy potential from sewage sludge. Because of the dependence of sewage sludge with population, the geographical distribution is similar to that for MSW.

Fig. 4 shows the generation-cost curve for sewage sludge. In spite of assuming the same costs as for anaerobic digestion of OFMSW, the minimum cost of electricity obtained from sewage sludge is a somewhat higher, 0.11 €/kWh, than from OFMSW. This is an effect of the scale economy present in anaerobic digestion plants. Plants for the treatment of sewage sludge are smaller than the corresponding ones for OFMSW because the lower energy potential of the sludge; and, as Table 4 indicates, smaller plant sizes lead to higher specific costs.
of centralized anaerobic digestion plants (where OFMSW, sewage sludge and livestock manure are combined) could lead to these cost reductions for this technology.

References


