Energy potential estimates for agro-industrial residues in Spain

Javier Zubizarreta[a], Antonio Gómez[a], Marcos Rodrigues[a], César Dopazo[a], Norberto Fueyo[*,a]

[a] *Fluid Mechanics Group (University of Zaragoza)*
María de Luna 3, 50018, Zaragoza, Spain

Abstract

In this paper, we assess the potential for the generation of electricity in Spain from agro-industrial residues. The industries considered are olive-oil mills, rice mills, wineries, dairy plants, breweries and wood, meat and nut processing plants. The methodology used is based on statistical data, and is integrated into a Geographical Information System (GIS) from which geo-referenced results are obtained. We estimate the overall energy contents of the residues (the primary-energy potential) and we carry out an economic analysis of the electric generation from them. The waste-to-electricity technologies analyzed are: grate firing followed by steam turbine, co-firing in coal power plants and anaerobic digestion plus internal combustion engine. The combined potential for the agro-industrial residues in Spain is estimated at 2625.7 $ktoe/y$ of primary energy representing 1.77% of the primary-energy consumption in Spain in 2007. Olive-mill and wood processing residues have the largest energy potentials. Comparisons are presented with (partial) results from other studies. Considering only economic profitable plants, grate-firing followed by steam turbine is the conversion option with a large potential, totalling 653 MW_e and an electric generation of 4.57 TWh (1.45% of the gross electric generation in Spain in 2007). Finally, a complete sensitivity analysis is done to investigate the influence of the economic parameters into the economic profitability of electric

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[*] Corresponding author. Tel: +34 976762153; fax: +34 976761882.
Email address: `Norberto.Fueyo@unizar.es` (Norberto Fueyo)

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generation from agro-industrial residues. Thus, a reduction of 50% of investment costs of grate firing technology makes that electric power of profitable plants increases to 1102 MW_e (being the electric generation of 7.70 TWh).

Key words: Biomass energy, Agro-food industry, Electricity, Renewable energy, GIS

Nomenclature

a annuitization factor

A fraction of oil per unit mass of olives ($t\ oil/t\ olives$)

B fraction of wine per unit mass of grapes ($t\ wine/t\ grapes$)

C fraction of methane in the biogas produced ($m^3\ CH_4/m^3\ biogas$)

C_B biomass generation cost (€/year)

C_{CF} electricity cost by co-firing (€/kWh)

$C_{inv,AD}$ investment cost for an AD/ICE plant (€)

$C_{inv,CF}$ investment cost for a CF/PC plant (€)

$C_{inv,GF}$ investment cost for a GF/ST plant (€)

D fraction of residue generated per unit mass of total byproducts ($t\ residue/t\ byproducts$)

E fraction of dairy wastewater per unit volume of milk ($m^3\ wastewater/m^3\ milk$)

F production of brewery residue per unit volume of beer ($t\ brewery\ residue/m^3\ beer$)

$FP_{r,p,CF}$ potential share (by co-firing) of the residue r generated in the province p in the coal power plants of the province p

G biogas production per unit mass of brewery residue ($m^3\ biogas/t\ brewery\ residue$)

h_{AD} operating hours during a year of an AD/ICE plant (hours/year)

h_{CF} operating hours during a year of a CF/PC plant (hours/year)

h_{GF} operating hours during a year of a GF/ST plant (hours/year)

H organic polluting content per unit volume of dairy wastewater ($kg\ COD/m^3\ wastewater$)

i discount rate

M methane production per unit mass of organic content ($m^3\ CH_4/kg\ COD$)

N lifetime of a power installation (year)

NPV net present value

P fraction of penetration of a technology in the industry

P_B biomass price at the transformation plant (€/GJ)

$P_{c,p}$ electric power of coal boilers in the province p

P_{CF} electric power of the co-firing installation (MW_e)

P_h heat price (€/kWh)

$P_{r,p,GF}$ electric power of a GF/ST plant which use the residue r generated in the province p

$P_{r,f,AD}$ electric power of an AD/ICE plant which use the residue r generated in the factory f

PI profitability index

R annual final product production (t/y)

R_E annual income from the selling of generated electricity (€/year)

Q lower heating value (MJ/kg, GJ/m^3 or MJ/m^3)

T_E feed-in tariff (€/kWh)

TCI total capital investment (€/year)

TOC total operating cost (€/year)

α fraction of the total capital investment dedicated to O&M costs

η_{AD} electric efficiency of an AD/ICE plant

η_{CF} electric efficiency of a CF/PC plant

η_{GF} electric efficiency of a GF/ST plant

π energy potential of the residue in Spain ($ktoe/y$)

$\pi_{r,f}$ energy potential of the residue r generated in factory f (MWh/y)

$\pi_{r,p}$ energy potential of the residue r in province p (MWh/y)

Subscripts

AD relative to AD/ICE technology

c coal power plant

CF relative to CF/PC technology

CH_4 methane

E electricity

ex olive-oil-extraction technology

f factory

GF relative to GF/ST technology

h heat

p province

r residue

Superscripts

w residue type

m mechanical operation in the wood industry

n nut processing industry

Abbreviations

AD/ICE anaerobic digestion/internal combustion engine

AS almond shell

BIG/CC Integrated biomass gasification/combined cycle

BIG/ICE Integrated biomass gasification/internal combustion engine

BSG brewers' spent grain

CF/PC Co-firing in pulverized coal boilers

CHP Combined heat & power

COD chemical oxygen demand

GC/ST grate combustion/steam turbine

GIS geographic information system

GP grape pomace

HS hazelnut shell

IDAE Institute for Diversification and Saving of Energy

MITYC Spanish Ministry of Industry, Tourism and Trade

MMA Spanish Ministry of the Environment and Rural and Marine Affairs

OH olive husk

O&M Operation and maintenance

OMW olive-mill wastewater

REE Spanish Electric Grid

UNESA Spanish Electric Industry Association

UHT ultra high temperature

1. Introduction

The European Union is promoting a global target of 20% of renewable energy in the final energy consumption by 2020. In addition, the Spanish government has set ambitious goals in renewable-energy production for the period 2005-2010 (IDAE, 2005) and beyond. Biomass-to-electricity is a well-known electricity-generating option but for the time being it does not appear to be playing the important role in the renewable energy mix that was expected. For waste biomass, the goal was an increase of 200 MW in installed power from agro and forest industry residues in 2010. In order to support policy decisions leading to realistic targets, it is important to accurately estimate the potential and costs of the electricity-generation from this kind of industrial waste.

In terms of turn-over, the Spanish food and beverage industry ranks the fifth in the European ranking, as well as leading the national industrial sector with 17% of total production in 2006. Furthermore, it underwent a production increase of about 4 percent in that year (MITYC, 2007a). The agro-food sector encompasses a broad variety of manufacturing processes that generate considerable quantities of different wastes, but especially organic residues, with an annual production of 2.43 million tonnes in 2005. In the last decades, the European legislative requirements for waste disposal are becoming increasingly restrictive (European Council, 1999); accordingly, there is a pressing need for the proper disposal of waste material. A number of studies in the literature conclude that agro-industrial residues are a suitable source of biomass for electricity production (Caputo et al., 2003; Kuiper et al., 1998; Boateng et al., 1992; Malaspina et al., 1996; Mussatto et al., 2006); however, its use as an energy source is hindered by several limitations, such as for instance the seasonal supply of waste (correlated to the seasonality of the main product); or the high investment costs required for waste pre-treatment (IDAE, 2005).

Regarding the electricity-generation technology, combustion followed by a steam cycle is, as for fossil fuels, the most developed and worldwide used route for biomass (DeMeo, 1997). For instance, Caputo et al. (2003) highlight the advantages of employing thermochemical processes for the disposal of residues from olive-oil manufacturing, due to the substantial reduction waste volume and polluting substances, as well as the high energy recovery. However, it is also stated that the fraction of moisture in the material is a crucial parameter in the combustion efficiency and even feasibility. It is generally accepted that moisture contents greater than 65% impairs combustion as the moisture greatly delays the release of volatiles (Agarwal and La Nouze, 1989). Biochemical processes are more a suitable solution for the conversion into electricity of high-moisture residues. Specifically, anaerobic treatments followed by compost production appear to be in this case the preferred solution, with the added benefit of the additional revenues accrued through the sale of byproducts (Caputo et al., 2003). As a result, several anaerobic-digestion (AD) plants have been established in Europe with acceptable success and good growing expectations (IDAE, 2005). Table 1 shows the typical moisture contents of the residues considered in the present study. Moisture content data have been obtained from Celma et al. (2007), FAO (1990), González et al. (2006), Haykiri-Acma and Yaman (2007), Fang et al. (2004) and Santos et al. (2003).

In the present work, the potential of generation of electricity from organic residues generated in the most important Spanish agro-industries, namely olive-oil mills, rice mills, wineries, dairy plants, breweries, and wood, meat and nut processing industries is estimated. To do it, in the first part of the study, a methodology is developed, based on statistical data, for the evaluation of the energy potential of these residues. This methodology is integrated into a Geographic Information System (GIS) from which geo-referenced results are obtained. In the second part, an economic analysis of the electricity generation from these agro-industrial residues is carried out. As the energy potential data, geo-referenced results are obtained from the economic analysis. Thermochemical (grate combustion followed by steam turbine, GC/ST, and co-firing in pulverized coal power plants, CF/PC) and biochemical technologies (anaerobic digestion plus internal-combustion engine, AD/ICE) are considered for the conversion of agro-industrial residues into electricity.

There are few studies published in the open literature with estimates of energy potential from agro-industrial residues and economic analyses of the electricity generation from them at a country level. Among those which share some degree of commonality with the present one, the following are noteworthy. Celma et al. (2007) evaluated the potential and profitability of the production of electricity from olive-mill and winery residues in Extremadura (a region of Spain), Matteson and Jenkins (2007) evaluated the potential and cost of the production of electricity from food-processing residues in California (United States of America) and Penniall and Williamson (2009) analysed the feasibility of gasification plants in the New Zealand wood-processing industry. At a local level, these kind the studies are more common, as for example, this carried out by Boukis et al. (2009), in which the viability of a biomass-residues combustion plant is investigated. It is more common to find in the literature studies in which only the energy potential of biomass residues is calculated. Thus, Ericsson and Nilsson (2006) evaluated the energy potential from byproducts from the forest industry in the European countries; Siemons et al. (2004) reported the potential of the wood-processing-industry residues also in the European countries, while AFB-NET (2000) presented a similar study for Spain; IDAE (2005) calculated the potential in Spain and in some of the Spanish Autonomous Communities from residues from olive-oil manufacturing and from wood processing; Andalusian Energy Agency (2007) reported the potentials from residues from olive-mill, and from the nut-, rice- and wood-processing industries in Andalusia (Spain); and Matsumura et al. (2005) evaluated the potential from different biomass in Japan. The methodology used for these studies is mainly statistical, and, in general, the results are not geo-referenced.

2. Methodology for energy potential

For the assessment of energy potential of agro-industrial waste we use a methodology that estimates the maximum amount of energy available from each source of residues. Generally, the energy potential of a source of residues results from two basic estimations: the amount of residues generated in a given temporal cycle (typically one year) with a certain geographical disaggregation, and the energy content of the material which is transformed into electricity.

2.1. Olive-mill residues

The production of olive-mill waste has risen sharply in the last four decades, especially in the Mediterranean area where most of worldwide olive-oil production takes place. Kapellakis et al. (2006) attribute this growth mainly to the industrialization of the agricultural sector and to the development of the oil-extraction technology. Waste disposal has become a major concern for olive-oil producers due to its polluting power and to the increasing severity of the applicable legislation.

According to IDAE (2005), olive-oil milling is the most attractive agricultural sector for energy recovery from residues in Spain. In general, three different residues are generated: olive husk (OH), olive-mill wastewater (OMW) and sludge. OH is a solid waste containing the pulp, the tegument and the stone of the olive. Traditionally OH has been used as animal feed but nowadays it is carried to seed-oil factories where the small percentage of residual oil it contains is extracted. As a result an easy-to-burn material is obtained (Caputo et al., 2003). OMW is made up of the water contents of the olive and frequently of some additional fresh water added in the process. It presents high biological and chemical pollutant load and it has been commonly used for fertilizing irrigation. Finally, the sludge is a byproduct similar in appearance to a mixture of OH and OMW (MMA, 2000). Some studies have suggested several physical and chemical treatments for these residues, e.g. lagooning, concentration by evaporation, ultrafiltration/reverse osmosis, or waste-to-energy processes such as incineration or aerobic/anaerobic digestion (Vitolo et al., 1999).

For the assessment of the amount of residues generated some considerations must be made. The types and quantities of residues obtained from olive mills depend greatly on the oil extraction system installed at the facility. There are currently three different extraction technologies commonly used in the Mediterranean basin, each one presenting different degrees of regional penetrations. These three technologies are the olive press, the three-phase system and the two-phase system (MMA, 2000). The press is the traditionally-used system, consisting in the crushing of the pulp by sequential pressing cycles with hydraulic devices. In this process, all three byproducts are generated: olive oil, OH and OMW. From the 70's, presses have been increasingly replaced by continuous systems, while they are still used in small production facilities. Continuous systems use centrifuges for the extraction of the byproducts permitting lower operating costs and higher performance and production rates. For a couple of decades the most successful of these resulting techniques was the three-phase system, which is based on the separation of byproducts by horizontal centrifuges called decanters. The byproducts of the three-phase system are oil, OH and OMW as in the traditional system. Finally, the *two-phase system* was developed in the early 90's as an evolution of the three-phase system with the intent to reduce the amount of waste generated, especially of OMW given its highly-polluting nature. The main innovation of this technique is that it eliminates the need to add hot water in the process. It results in less polluting production, higher processing capacity and slightly higher quality of the olive oil. Only two byproducts are generated in this process, oil and sludge. The two-phase system is currently the most widely-adopted process in the Spanish oil industry, accounting to three-quarters of the total olive oil production. Table 2 shows the values considered in this study for the distribution of byproducts per unit olive weight entering the mill for the different extraction systems, as reported by Caputo et al. (2003), and their corresponding penetration in the Spanish olive-oil sector (Celma et al., 2007). (The breakdown for the three-phase system exceeds 100% because some water is added in the process for the washing of the raw material.).

The energy potential of olive-mill residues is computed in this work from provincial data as follows:

$$\pi = \sum_{p} \sum_{r} \sum_{ex} \frac{R_p}{A} D^{w}_{ex} P_{ex} Q^{w} \tag{1}$$

where R_p is the annual olive-oil production in province p ((MMA, 2007)), A is the fraction of oil produced per unit olive treated, 0.20 (Caputo et al., 2003), D^{w}_{ex} is the fraction of the residue type w per unit weight of olives using the extraction technology ex (Caputo et al., 2003), P_{ex} is the penetration of the extraction system ex, Q^{w} is the lower heating value of the residue type w, 8.87 MJ/kg for OH, 1.59 MJ/kg for OMW and 7.75 MJ/kg for sludge, (Celma et al., 2007).

2.2. Winery residues

Spain is a major wine producer in the world, manufacturing more than 41 million hectolitres of wine and grape juice in 2005 (MMA, 2007). The residues generated in wine-making include grape stalk, grape pomace (GP) and wine lee. GP is the most significative one, with a worldwide generation about 7 million tons each year (Baumgartel et al., 2007). Its dumping results in environmental impacts owing its polluting characteristics such as low pH and high content of phytotoxic and bacterial phenolic substances. GP and wine lee have often been used for the distillation of spirit beverages, but current European legislation is more restrictive in this respect, prompting their processing in distilleries to obtain ethanol and brandy (European Council, 1999). Their use as animal feed or fertilizer has also been traditionally very common in the Mediterranean region. Other treatments for GP have been also suggested, including the recovery of valuable antioxidant polyphenols (Amico et al., 2008), or direct combustion (Celma et al., 2007).

In this study, the national energy potential of GP is calculated from provincial data as follows:

$$\pi = \sum_{p} 2 \frac{R_p}{B} D Q \tag{2}$$

where R_p is the annual wine and grape juice production in province p (MMA, 2007), B is the fraction of wine produced per unit grape pressed, 72% (Celma et al., 2007), D is the fraction of GP per unit weight of grapes generated in the pressing of grapes, 14% (Celma et al., 2007)), Q is the lower heating value of wine residue, 7.40 MJ/kg (Celma et al., 2007). A factor of 2 is included in the equation because the washing of the GP requires an important amount of water, some of which remains as moisture in the residue; hence, its final weight is about twice of the initial before washing (Celma et al., 2007).

2.3. Residue from forest-operation and wood-processing industries

This section considers the energy contents of residues from the forest operations (such as logging for timber) aimed at producing raw materials for subsequent industries, and of the wood-processing activities of these industries resulting in semi-finished products used to manufacture final wood products. Wood processing is a basic sector closely related to the building industry which has exhibited a considerable increase in the production of plywood and particleboard in Spain in the last years (MITYC, 2007a). Several residue types are generated both in the harvesting of timber and in mill-site operations, such as branches, needles, leaves, bark, sawdust, sunderdust, fines or trimmings. Due to their wide-ranging characteristics, these residues are usually classified according to the mechanical operation from which they are generated. The residues considered in this work are: forest residues, sawmilling residues, plywood manufacturing residues and particleboard manufacturing residues (FAO, 1990). The wood-processing industries in developed countries attempt to make an exhaustive use of their waste by burning it in hog fuel furnaces, thus helping to offset the cost of expensive fossil fuels. The residues often do have alternative uses such as building materials, fuelwood or pulp manufacturing; their final use varies with market location and demand (FAO, 1990).

The energy potential of wood processing residues is calculated in this work from each mechanical operation m and province p as follows:

$$\pi = \sum_{p} \sum_{m} R_p^m D^m Q^m \tag{3}$$

where R_p is the annual production of wood in the province p consumed in the mechanical operation m (MMA, 2007), D^m is the percentage of residue from mechanical operation m per unit volume of wood processed, taken as 30%, 43%, 45% and 5% for forest, sawmilling, plywood and particleboard residues respectively (Ericsson and Nilsson, 2006; FAO, 1990), Q is the lower heating value of the residue from mechanical operation m, 6.8 GJ/m^3 for forest residues and 7.2 GJ/m^3 for sawmilling, plywood and particleboard manufacturing residues (Ericsson and Nilsson, 2006).

2.4. Nut-processing residues

Nut-processing residues, together with olive mill effluents, are the most relevant source of biomass for electricity production from agro-food industries in Spain (IDAE, 2005). The large quantities of product generated and its low market value foster the recovery of energy from nut residues. Two nuts are considered here, viz almond and hazelnut, since they have by far the largest production in Spain (MMA, 2007); nougat (Spanish: turrón) producers are the main consumers of almond and hazelnut. Spain is the second world producer of almonds with a mean production of 75,000 t/y and the fourth one of hazelnut with 8,000 t/y; this is an indication of the importance of the nut processing industry in the Spanish food sector.

The main almond and hazelnut residues are generated in post-harvesting processing facilities. These facilities are basically divided into two types, hullers and huller/shellers. Hullers remove the outer covering of the nut by cracking it with hulling cylinders obtaining an in-shell nut. Huller/shellers involve a more complete process as the nut meat is also removed from its shell (EPA, 2000). Typically, hulls are sold as an ingredient for animal food while a number of studies suggest the use of shells as fuel in thermochemical processes (González et al., 2006, 2004; Haykiri-Acma and Yaman, 2007; Demirbas, 2004). Accordingly, we therefore consider the energy potential of almond and hazelnut shells (AS, HS) for all the Spanish nut production, which is estimated as follows:

$$\pi = \sum_{p} \sum_{n} R_p^n D^n Q^n \tag{4}$$

where R_p^n is the annual nut consumption by processing industry n in province p (MMA, 2007), D^n is the percentage of nut residue per unit weight of nut in the nut processing industry n, equal to 50.0% and 46.4% for almond and hazelnut respectively (Di Blasi et al., 1997; Ozdemir and Akinci, 2004), Q^n is the lower heating value of the residue from nut processing industry n, taken as 18.8 and 17.5 MJ/kg (Demirbas and Akdeniz, 2002; Haykiri-Acma and Yaman, 2007).

2.5. Rice-mill residues

Rice-milling residues, namely straw, stalk and rice husk, are the most important agricultural residue by quantity in the world, representing 43% of the total residues generated. Asia accounts for more than 92% of the world's rice milling residues, while Europe contributes under 0.5% (Werther et al., 2000). Rice husk is the outer cover of the rice and one of the most attractive residues for energy recovery through thermochemical processes due to its high availability (some large mills process 10-20 t/h), its large heating value of 12-18 MJ/kg, and its high volatile-matter content (Mansaray and Ghaly, 1998; Armesto et al., 2002; Kueng Song Lin et al., 1998; Fang et al., 2004; Maiti et al., 2006). The energy potential of rice-mill residue is calculated in this work from provincial data through the equation:

$$\pi = \sum_p R_p D Q \tag{5}$$

where R_p is the annual production of rice in province p (MMA, 2007), D is the percentage of residue per unit weight of byproducts, equal to 20% (Beagle, 1978), Q is the lower heating value of the residue of paddy rice, 12.3 MJ/kg (Fang et al., 2004).

2.6. Wastewater from the meat-processing industry

The meat sector is the largest producer in the Spanish food-industry sector, representing 19.7% of the total sales (FIAB, 2006). This leading industry generates large quantities of highly polluting residual wastewater, mainly from several process facilities in slaughterhouses, such as blood rafts and meat and guts washing rooms. Most meat processing-plants include a sewage-treatment facility within the complex, as it is often compulsory to treat wastewater separately before pouring it into the public sewage system. Aerobic digestion has been traditionally the most widely-used biochemical treatment for wastewater (Tritt and Schuchardt, 1992), although a combination of anaerobic and aerobic lagoons are more common in some countries, e.g. in the United States (Rodríguez Rebollo, 1998). The benefits of developing anaerobic systems have been studied by Salminen and Rintala (2002); Borja et al. (1998); Massé and Masse (2001) and Caixeta et al. (2002), but such systems have not been extensively used on a large scale despite their benefits of biogas production and decreased generation of sludge.

The energy potential of meat processing wastewater is calculated as follows:

$$\pi = \sum_{p} R_p E P M Q_{CH_4} \tag{6}$$

where R_p is the annual meat production from animal carcasses from slaughterhouses in province p (MMA, 2008a), E is the volume of wastewater generated per unit weight of meat, taken as 16 m^3/t (Rodríguez Rebollo, 1998), P is the organic polluting content of wastewater, 5.05 kg COD/m^3 (Borja, 1995), M is the production of methane per unit mass of organic content, equal to 0.297 m^3/kg COD (Fountoulakis et al., 2008), Q_{CH_4} is the lower heating value of the methane (37.2 MJ/m^3).

2.7. Dairy wastewater

The diary sector ranks third among the Spanish food industries, representing 10.3% of total sales, despite the massive closure of diary operations since the 90's due to the decrease in production allocation from the European Union (FIAB, 2006; COAG, 2006). Dairy industry production includes UHT, pasteurized, condensed, skimmed and powdered milk (accounting for 78% of the industry) and other products such as cheese, desserts, cream and butter (Vidal et al., 2000). Dairies generate wastewater flows with characteristics heavily dependent on the products, the processing methods and even the season of the year. This variability modifies the organic loading rate of wastewater, and for this reason the choice of optimal treatment method for the plant is not straightforward. In general, several methods are suitable for dairy wastewater treatment including reutilization of waste components, aerobic digestion and primary physical/chemical treatments. However, a prominent focus on anaerobic digestion has recently taken place due to the lower quantities of sludge generated and the absence of aeration compared with aerobic digestion (Vidal et al., 2000).

The energy potential of dairy wastewater is calculated from provincial data as follows:

$$\pi = \sum_{p} R_p E H M Q_{CH_4} \tag{7}$$

where R_p is the annual milk production in province p (MMA, 2008a), E is the volume of wastewater generated per unit volume of milk, taken as 3 $\mathrm{m}^3/\mathrm{m}^3$ (AINIA, 1997), H is the organic polluting content of wastewater, taken as 4.44 kg COD/m^3 (Janczukowicz et al., 2007), M is the production of methane per unit mass of organic content, 0.371 m^3/kg COD (Haridas et al., 2005), Q_{CH_4} is the lower heating value of the methane (37.2 MJ/m^3).

2.8. Brewery residues

Spain is the third beer producer in the European Union and the ninth in the world. The beer sector is very prominent in the Spanish industry, with an input to the economy of 5,100 M€/y, and generating ca. 8,000 direct jobs and more than 200,000 indirect jobs (MMA, 2008a). The brewing industry generates three main residues: spent grains, spent hops and yeast. The industry makes a proficient reuse of the last two since they can be composted or used as soil amendment or food for livestock.

Large quantities of brewers spent grain (BSG) are produced with more difficulties for its proper disposal, due to environmental problems and its scarce value as marketable product (Mussatto et al., 2006). Because BSG represents 85% of the residues generated by breweries, several possible uses have been proposed, such as a food ingredient for animal fodder, a fuel for energy production, a component for brick manufacturing or charcoal production. For energy recovery from BSG, thermochemical and biochemical processes are often considered as most viable, although most studies have focused on biogas production with heat recovery (Yu and Gu, 1996; Cronin and Lo, 1998; Alvarado Lassman et al., 2008).

The energy potential of brewery residue is estimated from provincial data using the equation:

$$\pi = \sum_{p} R_p F G C Q_{CH_4} \tag{8}$$

where R_p is the annual beer production in province p (MMA, 2008a), F is the production of brewery residue per unit volume of beer, 200 kg/m^3 (Mussatto et al., 2006), G is the production of biogas per unit BSG, 34.76 m^3/t (Ezeonu and Okaka, 1996), C is the percentage of CH_4 in the biogas produced, taken as 0.60 (Mussatto et al., 2006), Q_{CH_4} is the lower heating value of methane (37.2 MJ/m^3).

3. Methodology for the economic analysis

In this section, the methodology used to carry out the economic analysis of the production of electric energy from agro-industrial residues is described.

An economic analysis of the use of biomass for the production of electricity must to consider, among other factors, the characteristics of the residue (as for example, moisture content and lower heating value), its geographical dispersion, the technology for the transformation into electricity (which, at the same time, depends on the properties of the residue), the economy of scale of the transformation plant and the received feed-in tariffs. In this work, we have incorporated all this factors in the economic analysis to get an estimate of the production of electricity from agro-industrial residues which would be feasible in Spain.

For olive-mill residues, winery residues, residues from wood-processing industries, nut processing industries and rice-mill residues, we have considered two possible options to generate electricity: grate-fired combustion followed by a steam turbine (GF/ST) and co-firing in pulverized coal boilers (CF/PC). For brewery residues and wastewater from dairy products and meat-processing industries, we have considered anaerobic digestion plus an internal combustion engine (AD/ICE) for the production of electricity due to their high moisture content. Further, anaerobic digestion would form part of the process for compulsory treatment of wastewater before pouring it into the public sewage system. For these residues, conversion plants are located in the own factories.

Obviously, there are other options to transform residues into electricity as for example fluidized bed combustion followed by a steam turbine (FBC/ST), gasification with an internal combustion engine (BIG/ICE) and gasification/combined cycle system (BIG/CC). FBC/ST is a proved technology and has better electric efficieny than GF/ST (Celma et al., 2007; Dornburg and Faaij, 2001); on the other hand, it requires higher investment costs (Dornburg and Faaij, 2001; Celma et al., 2007) and its profitability is lower than GF/ST (Celma et al., 2007). BIG/ICE is a technology that is commercially available, but its deployment is stalled due to technical problems (it requires a high quality fuel and a careful operation) and economic aspects (it requires a high investment) (Faaij, 2006). Finally, BIG/CC is a promising technology with higher electrical efficiencies than the other ones, but it is yet in a demonstration phase. It has to face important technical problems, as for example, the cleaning of gases, and further, developed projects have needed important investments (Faaij, 2006). For these reasons, the probability of deployment of these technologies in the short-medium term is low, and therefore, these technologies have not been included in the economic analysis.

Next, we describe the economic analysis done for the three conversion technologies chosen.

3.1. Firing-grate combustion

This option is considered for olive-mill residues, winery residues, residues from forest-operation and wood-processing industries, nut processing industries and rice-mill residues. To do the economic evaluation we have considered that the residues generated in each province are used in the same province for the production of electricity. Taking this into account, we first calculate the electric power of a GF/ST plant in each province as:

$$P_{r,p,GF} = \frac{\pi_{r,p}}{h_{GF}}\,\eta_{GF} \tag{9}$$

where $P_{r,p,GF}$ (MW) is the electric power of a GF/ST plant which use the residue r generated in the province p, $\pi_{r,p}$ $(MW_{th}/\,year)$ is the energy-potential of the residue r in the province p (calculated with the methodology described in section 2), h_{GF} (hours/year) are the operating hours during a year and η_{GF} is the electric efficiency of the GF/ST plant. Hours/year and electric efficiency considered for this technology are shown in Table 5. The expression used to calculated the electric efficiency is obtained from Celma et al. (2007). Electric efficiency of these kind of installation diminishes as electric power do so (Dornburg and Faaij, 2001; Celma et al., 2007; Bridgwater et al., 2002; Resch et al., 2006); this increases the importance of economies of scale for these plants. The maximum electric power considered is 25 MW_e; this maximum size is fixed taking into account the current size of this installations and the feed-in tariffs in Spain are only given to renewable installations with electric power under 50 MW_e (MITYC, 2007b). Larger sizes of biomass-to-electricity plants involve an increase of the risks, as for example, a temporary lack of residues. If energy potential is enough, several installations GF/ST plants are considered. Once electric power of a transformation plant is obtained, the economic profitability of each plant is calculated through the net present value (NPV) and the profitability index (PI).

Net present value is calculated as:

$$NPV = \sum_{t=1}^{N} \frac{[R_E - TOC]_t}{(1+i)^t} - TCI \tag{10}$$

where N is the lifetime of the installation (taken as 20 years), R_E (€/year) are the annual incomes from the selling of generated electricity (€/year), TOC (€/year) are the annual operating costs, including costs of residues and operating and maintenance costs, i is the discount rate (assumed as 9%) and TCI is the total investment costs (€).

Profitability index is defined as:

$$PI = \sum_{t=1}^{N} \left[\frac{[R_E - TOC]_t}{(1+i)^t} \right] / TCI \tag{11}$$

Total capital investment of GF/ST is calculated as $TCI = P_{r,p,GF} \cdot C_{inv,GF}$ where $C_{inv,GF}$ is the specific investment cost, calculated as a function of the electric power (Celma et al., 2007) (see Table 5). Revenues from selling electricity are calculated as $R_E = P_{r,p,GF} \cdot h_{GF} \cdot T_E$ where T_E is the corresponding feed-in tariff according to the residue, electric power and year life of the transformation plant. Feed-in tariffs are fixed by Royal Decree 661/2007 (MITYC, 2007b). As it is observed in Table 6, feed-in tariffs for agro-industrial residues are larger than wood-industry residues. Operating costs, TOC (€/year), include residues costs and O&M costs. O&M costs are calculated as a fraction of the total capital investment (TCI), $O\&M = \alpha \cdot TCI$, where α is the considered fraction. Different percentages are reported in the literature (Dornburg and Faaij, 2001; Celma et al., 2007; Resch et al., 2006), ranging between 3% and 6%. We have assumed α as 4%. Costs of residues are calculated as $C_B = P_{r,p,GF} \cdot h_{GF} \cdot 3.6/\eta_{GF} \cdot P_B$ where P_B is the price of the residues (€/GJ) at the transformation plant. The price of the residues depends on the alternative uses of them, which provide an economic value for them, the cost of the transport from the place where them are generated to the transformation plant, and the moisture content (in the case that residues will be used in combustion plants), since removing the moisture from a residue will involve an economic cost. All these factors make the price of the residues highly dependent on the local conditions where them are generated and used. Celma et al. (2007) reported prices of 2.05 €/CJ for grape waste, 3.28 €/GJ for OH, 2.67 €/GJ for olive sludge and 8.09 €/GJ for OMW; Siemons et al. (2004) reported costs of solid industrial residues (mainly residues from wood-processing industry) between 1.38 - 2.28 €/GJ in Spain. Table 7 shows the assumed cost for the residues considered in this work.

Figure 1 shows the economic methodology used in this work for GF/ST and CF/PC options. As a result, the location (province), power and electric generation of profitable GF/ST plants (NPV>0) feed with the main agro-industrial residues in Spain is obtained. Finally, a sensitivity analysis is carried out to treat the uncertainty of parameters as cost of residues, investment costs, O&M costs and discount rate.

3.2. Coal co-firing

This option is considered for olive-mill residues, winery residues, residues from forest-operation and wood-processing industries, nut processing industries and rice-mill residues. In first place, information about coal power plants in Spain is obtained: location, electric power and lifetime (UNESA, 2007). After it, we have considered for the economic analysis only coal power plants whose lifetime is extended, at least, until 2020. Table 8 shows the electric power of coal boilers that will be working by 2020 and the province where are located. It is observed that these coal power plants are concentrated in only 8 provinces (of the 50 provinces of Spain). Next, in these provinces, the electric power that could be substituted by generated residues in the respective province is calculated. To do this, we use equation 12:

$$FP_{r,p,CF} = \frac{P_{c,p}}{(\pi_{r,p}/h_{CF})\ \eta_{CF}} \tag{12}$$

where $FP_{r,p,CF}$ is the fraction of electric power of the coal power plants in the province p that could be substituted by residue r generated in the same province p, $P_{c,p}$ is the electric power of coal boilers in the province p, h_{CF} (hours/year) are the operating hours of coal power plants during a year and η_{CF} is the assumed electric efficiency of a co-firing installation, 0.38 (Resch et al., 2006). Operating hours of coal power plants have fluctuated considerably in the last years; thus, in 2007, the average operating hours of coal power plants in Spain were 6 375 hours (MITYC, 2008a), and in 2008, were 4 200 hours (REE, 2009). These differences are caused by annual variations of gas natural price, ton CO_2 price and hydraulic generation. The progressive installation of combined cycles in Spain (UNESA, 2007), probably, will reduce the operating hours of coal power plants. Taking that into account, we have assumed 4 000 hours by year.

Royal Decree 661/2007 (MITYC, 2007b) does not fix feed-in tariffs for co-firing plants; it states that these installations could receive feed-in tariffs and them will be calculated for each specific case. Therefore, in spite of calculating the profitability of the co-firing installations, we have calculated the cost of the electricity generation by co-firing residues. Moreover, a sensitivity analysis is carried out to study the influence of different parameters in that cost.

To calculate the electricity cost by co-firing residues, we use equation 13:

$$C_{CF} = \left(a \cdot TCI + TOC\right) / \left(P_{CF} \cdot h_{CF}\right) \tag{13}$$

where C_{CF} is the cost of the electricity generated by co-firing €/kWh, a is the annuitization factor, given by $a = r/\left(1 - 1/\left(1+i\right)^N\right)$, where i is the nominal discount rate (taken as 9%) and N is the investment lifetime (10 years); and, P_{CF} is the electric power of the co-firing installation. Total capital investment is calculated as $TCI = P_{CF} \cdot C_{inv,CF}$ where $C_{inv,CF}$ is the specific investment cost of a co-firing installation. It depends on the type of coal power plant (Berggren et al., 2008) (fluidized bed, fired-grate or pulverized coal) and the co-firing system (direct, indirect or parallel)(García, 2006). Further, inside each type of co-firing systems, there are variations; for example, in direct co-firing systems, the biomass could be introduced into the boiler by the same burners as coal, or, by a new burner (only for biomass) (Hughes, 2000). For these reasons the range of specific investment costs reported for co-firing installations is wide, from 100 €/kW to 880 €/kW (Faaij, 2006; Ericsson, 2007; Berggren et al., 2008; García, 2006); for direct co-firing systems (which requires a lower investment) and pulverized coal power plants (in Spain, all coal power plants are pulverized boilers) the reported range of $C_{inv,CF}$ goes from 100 €/kW to 550 €/kW. Thus, in this work, we have taken a specific investment cost of 300 €/kW (assuming direct co-firing systems). Residues cost is calculated as $C_B = P_{CF} \cdot h_{CF} \cdot 3.6/\eta_{CF} \cdot P_B$. The price of the residues, P_B could be higher for CF/PC than for a GF/ST since the location of a GF/ST plant could be optimised (to reduce transport costs) before the construction, but this is not possible for a co-firing installation. Nevertheless, we have assumed that prices are the same (see Table 7). O&M cost is considered as a fraction of the total capital investment, $O\&M = \alpha \cdot TCI$, where α is assumed as 4%.

Figure 1 shows the methodology used in this work for the analysis of the potential of CF/PC option. As a result, it is obtained: the share of agro-industrial residues in coal power boilers in Spain (considering only the residues generated in the same province where coal boilers are located) and the electricity generation cost.

3.3. Anaerobic digestion

This option is considered for brewery residues and wastewater from dairy products and meat-processing industries. To carry out the economic analysis, we have obtained information about typical size of slaughterhouses, dairy factories and breweries in Spain. Thus, there are nearly 1 200 slaughterhouses, though 80% of meat production is carried out by only 25 slaughterhouses, whose capacity ranges between 30 000 and 150 000 ton/year (Langreo, 2002). The situation of dairy sector is similar; there are 670 companies dedicated to elaboration of dairy products, but nearly 80% of production is controlled by 15 companies (MMA, 2008b), whose factories treat between 50 000 and 200 000 ton/year of milk. Finally, there are 21 breweries in Spain whose capacity of production ranges between 509 000 and 2 200 000 hl/year (Cerveceros de España, 2008). For the production ranges of slaughterhouses, dairy factories and breweries, we calculate the power of an AD/ICE plant that use the residues of these industries with equation:

$$P_{r,f,AD} = \frac{\pi_{r,f}}{h_{AD}}\,\eta_{AD} \tag{14}$$

where $P_{r,f,AD}$ (MW) is the electric power of a AD/ICE plant which use the residue r generated in the factory f, $\pi_{r,f}$ $(MW_{th}/\,year)$ is the energy-potential of the residue r generated in the factory f (calculated with equations 6, 7 and 8 using data of annual production of slaughterhouses, dairy factories and breweries), h_{AD} (hours/year) is the operating hours during a year and η_{AD} is the electric efficiency of the AD/ICE plant. Operating hours are fixed taking into account the labour activity of the factories (see Table 5). The electric efficiency is assumed considering the efficiency of an internal combustion engine (Flynn and Ghafoori, 2006).

Once it is determined electric power, the economic profitability of the AD/ICE system is obtained through the calculation of the net present value (NPV) and profitability index (PI) with equations 10 and 11. In these equations, total capital investment of AD/ICE is calculated as $TCI = P_{r,f,AD} \cdot C_{inv,AD}$ where $C_{inv,AD}$ is the specific investment cost, calculated as a function of the electric power (Walla and Schneeberger, 2008) (see Table 5). Revenues from selling electricity are calculated as $R_E = P_{r,f,AD} \cdot h_{AD} \cdot T_E$ where T_E is the corresponding feed-in tariff (MITYC, 2007b) according to the electric power of the transformation plant and year life of the generation plant. Feed-in tariffs for electricity production from biogas are shown in Table 6. Additionally, we have calculated the economic profit in the case that the generated heat from AD/ICE system is used by the own factory or it is sold. In this case, revenues include the economic value of the generation of heat, calculated as $R_H = P_{r,f,AD}/\eta_{AD} \cdot \eta_{h,AD} \cdot h_{AD} \cdot P_h$ where R_H are the economic revenues from heat, $\eta_{h,AD}$ is the heat efficiency of the AD/ICE system and P_h is the price of heat. Heat efficiency is assumed to be 40% (Murphy et al., 2004) and the price of heat is considered as 0.06 €/kWh. O&M costs are calculated as a fraction of the total capital investment (TCI), $O\&M = \alpha \cdot P_{r,p,GF} \cdot C_{inv,AD}$, where α is taken as 6% (Resch et al., 2006). Cost of residues is considered as zero since AD/ICE plants are located in the own factories (therefore, transport costs are avoided) and it is not considered a value in origin for these residues.

Figure 2 shows the steps followed to carry out the economic analysis for AD/ICE electricity generation. As a result, power, electric generation and the economic profitability of AD/ICE plants are obtained as a function of the typical capacity of production of slaughterhouses, dairy factories and breweries in Spain. Additionally, a sensitivity analysis is carried out to treat the uncertainty of the investment costs, O&M costs, discount rate, operating hours and heat price. The presented results for AD/ICE installations are not geo-referenced since there are available geographical data about the production by province, but not for the location of the factories.

4. Results: energy potential

The combined potential for the agro-industrial residues is estimated at 2625.7 *ktoe/y* of primary energy; for the sake of comparison, this represents 1.77% of the primary energy consumption in Spain in 2007 (MITYC, 2008a). Table 3 shows the overall energy potential broken down by residue. Figures 3 and 4 show the geographic distribution of the energy potential of the residues. Olive mill, wood processing and winery residues have the higher potentials. Three Andalusian provinces, Jaén (187 *ktoe/y*), Córdoba (118 *ktoe/y*) and Seville (48 *ktoe/y*) exhibit the highest potential from olive mill residues. On the other hand, the largest potentials for residues from forest operations and wood processing industries are in the North-West of the country, corresponding to regions with wettest climate (Figure 3); Lugo, A Coruña and Asturias present 216, 214 and 124 *ktoe/y* respectively. The highest potential from winery residues is located in the provinces on the South sub-plateau of Spain (Castilla-La Mancha), Ciudad Real, Toledo and Cuenca with energy potentials of 66, 35 and 25 *ktoe/y* respectively. For this residue, the geographic dispersion is higher than the observed one for olive-mill and wood-processing residues.

The results obtained in the present contribution can be related to some other ones reported in previous studies by other authors; Table 4 presents a summary of the energy potentials. In addition to the results summarized in Table 4, the combined potential for olive mill residues and wood processing residues is estimated by IDAE (2005) at 2949 *ktoe* for Spain (compared with 2053 *ktoe* obtained in this study). In general, the results can be judged to be in good agreement, given that differences in the estimates can arise out of a multiplicity of factors (including the methodology used, the resource-availability data, or the heating value of the residues).

5. Results: economic analysis

In this section the results of the economic analysis for the considered options (GF/ST, CF/PC and AD/ICE) for electricity conversion of agro-industrial residues are presented.

5.1. GF/ST

Here, the results of the economic analysis of electricity generation from olive-mill, winery, wood-processing, nut-processing and rice-mill residues through GF/ST plants are presented. The results are shown separately for each residue. GF/ST plants feed with different residues have not been considered in this work.

5.1.1. Olive-mill residues

Table 9 shows the location, electric power, electric generation, NPV and PI of the GF/ST plants feed with agro-industrial residues that have positive NPV. Figure 5 shows the electric power and location of these GF/ST plants.

We have calculated only 6 provinces (all of them located in the South of Spain, as it is seen in Figure 5) with profitable GF/ST plants feed with olive-mill residues, totalling 216.8 MW_e and an electric generation of 1.51 $TWh/year$. Respect to the energy-potential of this residue in Spain, 579.9 $ktoe/year$, this electric generation represents, approximately, a 22.3% of the primary energy of this residue. Figure 6 shows the number of GF/ST plants for different ranges of electric power calculated for the residues analysed in this work. Indirectly, Figure 6 indicates the geographical dispersion of the residues. Olive-mill residues are relatively concentrated since there are several plants with electric power over 20 MW_e and, at the same time, an important number of plants with electric power under 1 MW_e. This indicates that there are provinces with a high energy-potential of olive-mill residue while the rest of provinces have a very low energy-potential, as it also can be seen in Figure 3.

Figures 7, 8, 9 and 10 shows the influence in the profitability of GF/ST plants of the variation of the cost of residues, investment costs, O&M costs and discount rate, respectively. In the case of GF/ST plants feed with olive-mill residues, cost of residues and investments costs have the largest influence in the economic profitability; thus, a reduction of 50% of the investment costs increases the electric power of GF/ST plants with positive NPV to 268 MW_e; on the other hand, a increase of 50% of the investment cost diminishes the number of profitable GF/ST plants, totalling 125 MW_e. In terms of the electric generation of profitable GF/ST plants, it is increased to 1.87 TWh when investment cost is reduced the 50% from assumed values, and it is reduced to 0.875 TWh when investment cost is increased the 50%. The influence of discount rate is important too, but to a lesser extent that investment and residues cost. Among the analysed parameters, O&M costs has the lowest influence in the economic profitability.

5.1.2. Winery residues

There are only 3 provinces with profitable GF/ST plants feed with winery residues (as it is seen in Figure 5 and Table 9), totalling 53.4 MW_e and a generation of 0.373 $TWh/year$. Respect to the energy-potential of this residue in Spain, 282.4 $ktoe/year$, this electric generation represents, approximately, a 11.3% of the primary energy of the winery residues.

Energy-potential of winery residues is lower than olive-mill residues one and, as it can see in Figure 6, winery residues are more dispersed geographically than olive-mill residues. So, the GF/ST plants calculated for winery residues have electric power predominantly under 10 MW_e. This worses the economic profitability due to the effect of scale economies. Smaller GF/ST plants requires higher specific investment costs and has lower electric efficiencies. For these reasons, the electric generation of GF/ST plant with positive NPV represents a low fraction of the primary energy of the residues.

Investments costs have the largest influence in the economic profitability of GF/ST plants feed with winery residues; thus, a reduction of 50% of the investment costs increases the electric power of GF/ST plants with positive NPV to 118 MW_e; on the other hand, a increase of 50% of the investment cost makes that power of profitable GF/ST plants disminishes to 25 MW_e. In terms of the electric generation of profitable GF/ST plants, it is increased to 0.830 TWh when investment cost is reduced the 50% from assumed values, and it is reduced to 0.175 TWh when investment cost is increased the 50%. The influence of the cost of the residues and the discount rate is similar, but it is lower than the influence of investment costs.

5.1.3. Wood-processing residues

As it can be seen in Table 9 and Figure 5, there are 7 provinces (all in the North of Spain) with profitable GF/ST plants feed with wood-processing residues, totalling 375 MW_e and a generation of 2.625 $TWh/year$.

Respect to the energy-potential of this residue in Spain, 1473.0 $ktoe/year$, this electric generation represents, approximately, a 15.3% of primary energy. As it can be seen in Figure 6, wood-processing residues are geographically concentrated since there are a important number of power plants in the highest range of electric power (20-25 MW_e). However, the ratio of the electric generation/primary energy is lower (15.3%) than the corresponding one to olive-mill residues (22.3 %). The reason for this is the low profitability of wood-processing GF/ST plants. These plants have a low PI (1.07) compared to the olive-mill GF/ST plants PI (among 1.3 and 1.6). This is caused by the lower feed-in tariffs for production of electricity from wood-processing residues (see Table 6).

Investment costs and discount rate have the largest influence in the economic profitability of wood-processing GF/ST plants, as it can be seen in Figures 7, 8, 9 and 10. Thus, a reduction of 50% of the investment costs increases the electric power of GF/ST plants with positive NPV to 676 MW_e; on the other hand, a increase of 50% of the investment cost makes that no GF/ST plants have positive NPV. In terms of the electric generation of GF/ST plants with positive, it is increased to 4.73 TWh when investment cost is reduced the 50% from assumed values. The influence of cost of residues and O&M costs is important too, but to a lesser extent that investment cost and discount rate. The low profitability of GF/ST plants produces that a change of an economic parameter, as investment cost, could make that all GF/ST plants have a negative NPV.

5.1.4. Rice-mill residues

Only a GF/ST plant feed with rice-mill residues is calculated with a positive NPV (see Table 9). It is located in the South of Spain (see Figure 5) and has an electric power of 8.6 MW_e. Its electric generation is 0.06 $TWh/year$. Respect to the energy-potential of this residue in Spain, 52.8 $ktoe/year$, this electric generation is equivalent, approximately, to 9.7% of primary energy of rice-mill residues in Spain.

Rice-mill residues energy potential is low, and further, it is geographically dispersed (see Figure 6); as a result, nearly all calculated GF/ST plants have electric power under 5 MW_e. Scale economies is really negative for GF/ST plants with these sizes; and for this reason, the calculated ratio electric generation/primary energy is so low.

Investments costs and discount rate have the largest influence in the economic profitability (see Figures 7, 8, 9 and 10) as it is expected due to small sizes of GF/ST plants and the low cost of this residue (see Table 7). A reduction of 50% of the investment costs increases the electric power of GF/ST plants with positive NPV to 21 MW_e (0.14 TWh); on the other hand, a increase of 50% of the investment cost makes that no GF/ST plants have positive NPV.

5.1.5. Nut-processing residues

With the assumed economic parameters, all the calculated nut-processing GF/ST plants have negative NPV. Figure 6 shows that all calculated GF/ST plants feed with nut-processing residues have electric power under 5 MW_e. It is due to the low energy-potential of this residue and its high geographical dispersion. The small plant-sizes makes difficult to get an economic profitability for these plants.

Investment cost and discount rates are the economic parameters with a large influence in the economic profitability of these plants, as it is seen in Figures 7, 8, 9 and 10. This is expected due to the small sizes of the GF/ST plants and the low cost of the residue (see Table 7). In the best case, a reduction of 50% of the investment costs, the electric power of profitable nut-processing GF/ST plants increases to 16.8 MW_e (0.12 TWh).

5.2. Coal co-firing

In this section the results obtained for the coal co-firing of agro-industrial residues in Spain are presented. Table 10 shows the potential share of residues in coal power plants (considering only residues generated in the same province) whose lifetime will be extended, at least, until 2020. Assuming only CF/PC installations with substantial shares (more than 5%) and taken the maximum residues power share as 10% (higher residues share could reduce the efficiency of coal boiler (Tillman, 2000) and cause problems of corrosion (Sondreal et al., 2001)), co-firing power from agro-industrial residues rises to 430.9 MW_e and electric generation is up to 1.724 TWh (see Table 11). Figure 11 shows the location of these CF/PC installations.

Figures 12 and 13 show the electricity cost for co-firing wood-processing residues and olive-mill residues, respectively. We have extended the economic analysis only to these residues, since, as it can be seen in Table 10, only olive-mill and wood processing residues could have large shares in coal boilers. For both residues, operating hours is the parameter with the highest influence in the cost of electricity; investment costs and cost of residues have a considerable influence, too. For wood-processing residues, in most of the cases, electricity cost is under 0.035 €/kWh. For olive-mill residues, electricity cost is under 0.055 €/kWh in most of the range studied. Both costs are considerably lower than feed-in tariffs given for combustion of wood-processing residues and olive-mill residues.

5.3. Anaerobic digestion

In this section, the results of the economic analysis for production of electricity through the anaerobic digestion of brewery residues and wastewater from dairy products and meat-processing industries are presented. Table 12 shows the electric power, NPV if only electricity is produced, and, NPV and PI in the case that heat is used, of AD/ICE installation corresponding to different sizes of the generating-residues industries. The calculated electric power of

AD/ICE facilities for the considered sizes of the industries range from 0.135 to 2.32 MW_e, though in most of the cases, electric power is under 0.6 MW_e. In Table 12 is observed that the net present value of AD/ICE plants that produce only electricity is negative for all the cases. These installations are profitable only if generated heat can be used; further, in that cases, profitability index of 1.5 are achieved. It is observed that PI increases along with the increase of electric power due to the scale economies. Nevertheless, PI in the range of 0-0.5 MW_e are larger than for higher electric powers; this is caused by feed-in tariffs. As it is observed in Table 6, feed-in tariffs are higher in the range of 0-0.5 MW_e than for electric power greater than 0.5 MW_e.

A sensitivity analysis of the economic profitability of AD/ICE plants has been made. For it, a generic AD/ICE plants has been chosen with electric power of 0.1 MW_e, 0.25 MW_e, 0.5 MW_e and 1.0 MW_e. Figure 14 and 15 present this sensitivity analyisis, respectively in the case that only electricity is produced and in the case that heat is used or sold. The studied parameters are: investment costs, discount rate, O&M costs and operating hours. It is observed that investment costs and operating hours have the highest influence on the net present value. When only electricity is produced, the net present value is negative for most of the cases; conversely, net present value is positive for most of the cases when heat is used. Therefore, profitability of AD/ICE plants is highly dependent on the use of the generated heat; the feed-in tariffs are not enough to consider only the production of electricity. Figure 16 shows the NPV of the AD/ICE plants against heat price. It is observed that heat prices above 0.04 €/kWh makes net present value positive for all the range of AD/ICE electric powers.

6. Conclusions

In this study, the energy potentials from the organic residues of the most important agro-industries in Spain are estimated. These potentials are integrated into a GIS and the results obtained are geo-referenced. The agro-industries considered are: olive mills, wineries, wood-processing industries, nut-processing industries, rice mills, meat-processing industries, diaries and breweries. Using the estimated energy potentials, the profitability of the electricity generation from these residues is calculated. Three waste-to-electricity technologies, grate firing/steam turbine (GF/ST), co-firing in pulverized coal power plants (CF/PC) and anaerobic digestion/internal combustion engine (AD/ICE), have been considered. The two first ones, GF/ST and CF/PC, are analysed for the use of olive-mill, winery, wood-processing, nut-processing and rice-mill residues, and the last one, AD/ICE for the treatment of waste water of meat-processing industries, diaries and breweries industries.

Wood-processing and olive-mill residues are the largest contributors in the aggregated potential from agro-industry residues. This total potential is estimated at 2625.7 $ktoe/y$ of primary energy, which is equivalent to 1.77% of the consumption of primary energy in Spain in 2007 (MITYC, 2008a). The higher energy potential is located in the North-Western provinces of Spain (since them have the largest energy potential of wood-processing residues) and the South sub-plateau provinces of Spain (since them have the largest energy potential of olive-mill residues). The potentials found in this work are consistent with partial ones reported previously by other authors, within the variability resulting from the use of different methods and data sources.

The economic analysis for the GF/ST plants shows that 28 GF/ST plants have a positive net present value, totalling 653.6 MW_e and an electric generation of 4.574 TWh, 1.46% of the gross electric generation in Spain in 2007 (MITYC, 2008a). Olive-mill and wood-processing residues are the largest contributors to GF/ST power, 216.6 MW_e and 375.0 MW_e, respectively. However, the profitability of wood-processing residues GF/ST plants is lower than olive-mill residues GF/ST plants one. This is caused because feed-in tariffs for electricity produced by agro-industrial residues are higher than for wood-processing residues; and, in spite of wood-processing residues costs are lower, this does not offset the low feed-in tariff. This situation is reflected into the installed electric power that use agro-industrial residues as fuel in Spain. There are 206 MW_e of electric power installations feed with agro-industrial residues: 125 MW_e are feeded with olive-mill residues, 70 MW_e with wood-processing residues, 5.5 MW_e with winery residues, 3.3 MW_e with nut-processing residues and 2.2 MW_e with rice-mill residues (MITYC, 2008b; CNE, 2009). Therefore, there is a wide margin to increase the electric power and generation from these residues, specially for wood-processing residues. However, the low feed-in tariffs for the electricity generation from this resource slows down the deployment of power installations that use this residue. Respect to winery residues, nut-processing and rice-mill residues the energy potential is low and, besides, they are dispersed geographically. Due to it, calculated GF/ST plants have small electric powers (in most of the cases, under 10 MW_e or even lower) and for these plant-sizes the effect of scale economies is really negative for the economic profitability. Therefore, the use of these residues to generate electricity is not probable currently. A reduction of investment costs of small GF/ST plants or the development of small plant-sizes technologies with lower investment costs, as for example, small gasification plants plus an internal combustion engine, could improve the economic profitability of these residues. Biomass heating plants are another option for the contribution of energy generation; currently there are heat boilers feeded with almond shells in Spain (Rakos, 2003).

Respect to electricity generation by co-firing in coal power boilers, we have calculated the potential share of residues in coal power plants (considering only residues generated in the same province) whose lifetime will be extended, at least, until 2020. Assuming only CF/PC installations with substantial shares (more than 5%) and taken the maximum residues power share as 10% , we have estimated a potential of co-firing power from agro-industrial residues of 430.9 MW_e, with an electric generation of 1.724 TWh. Only olive-mill residues and wood-processing residues have enough enegy potential to have large shares in coal boilers. we have carried out an sensitiviy analysis of the electricity cost by co-firing using as fuel wood-processing residues and olive-mill residues. For wood-processing residues, in most of the cases, electricity cost is under 0.035 €/kWh. For olive-mill residues, electricity cost is under 0.055 €/kWh in most of the range studied. Both costs are considerably lower than given feed-in tariffs for combustion of wood-processing residues and olive-mill residues. herefore, CF/PC could be a profitable option, compared with combustion alone. However, the lack of regulation about co-firing (MITYC (2007b) does not specify any feed-in tariff for CF/PC, only it establishes that feed-in tariff will be calculated for each specific case) avoids the deployment of this option for residues. Currently, there are not co-firing installations working in Spain.

AD/ICE option is considered for brewery residues and wastewater from dairy products and meat-processing industries. The electric power of AD/ICE facilities has been calculated for the typical sizes of the industries. As a result, the electric power range goes from 0.135 to 2.32 MW_e, though in most of the cases, it is under 0.6 MW_e. For these installations without heat recovery, net present value is negative for all the range of electric powers. In the case that heat is used, AD/ICE installations are profitable if heat prices are above 0.04 €/kWh. It must be mentioned that AD/ICE plants form part of the waste water treatment system, but in this work, the profit due to the treatment of the waste water has not been accounted for. For this reason, profitability of AD/ICE plants could be higher than calculated one in this work. Nevertheless, the use of heat improves significantly the profitability of AD/ICE plants. Currently, the deployment of this technology is limited in Spain since factories use generally other treatment for waste water (as for example, aerobic systems), and, if their requirements of heat are high, use gas co-generation systems (which have feed-in tariffs, too).

To sum up, except for olive-mill residues, there is an important unused potential for generation of electricity from agro-industrial residues in Spain. There are different reasons for this: for wood-processing residues, the low feed-in tariffs produce a low economic profitability; for winery, nut-processing and rice-mill residues, the low energy-potential and high geographical dispersion cause an important negative effect of the scale economies in the profitability; the option of CF/PC is interesting, but the lack of regulation and of a fix feed-in tariff avoids its deployment; the installation of ADE/ICE plants depends highly on the possibility to use or sold the generated heat for the industry, and, besides, it must compete with other technologies that could develop the same work. Regulation, adequate feed-in tariffs and development of profitable technologies for small sizes of power plants could be the main tools to improve the energy use of agro-industrial residues.

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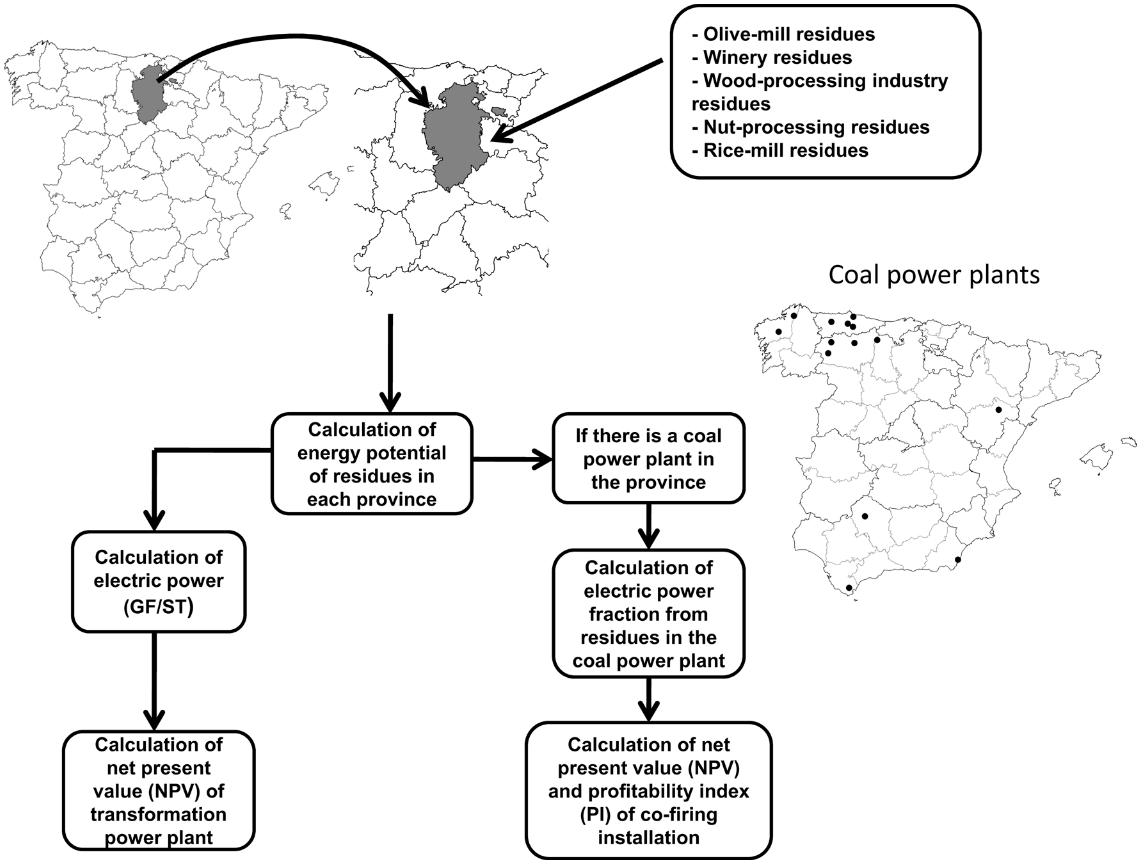


Figure 1: Methodology used for the economic analysis of GF/ST plants and CF/PC installations.

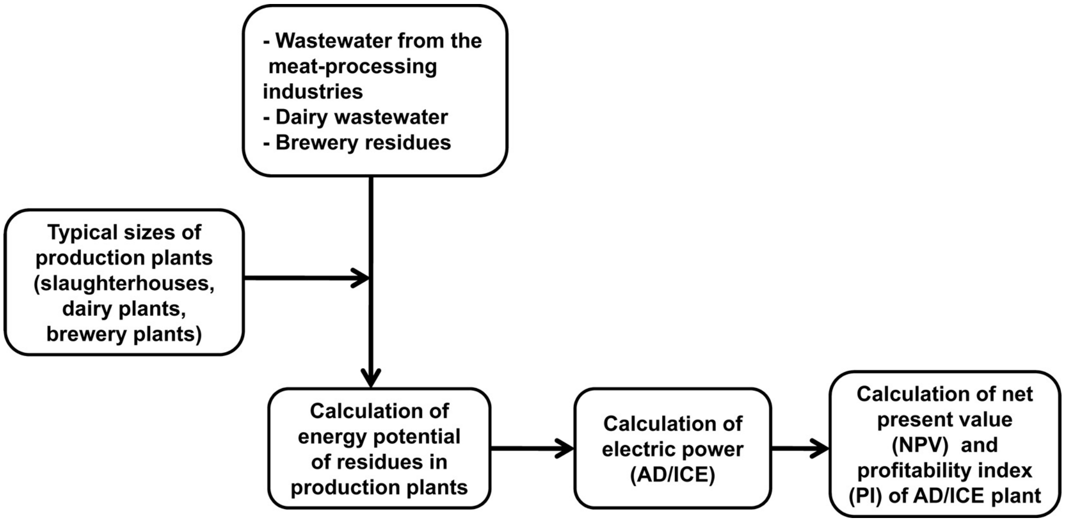


Figure 2: Methodology used for the economic analysis of AD/ICE plants.

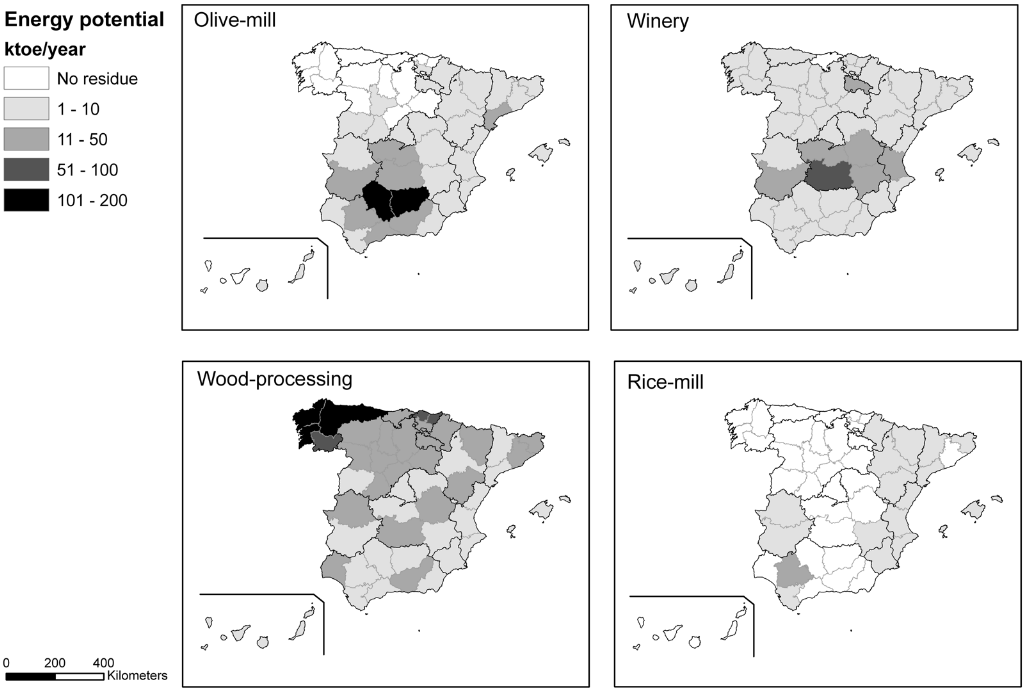


Figure 3: Geographic distribution of the energy potential of olive-mill, winery, wood-processing and rice-mill residues.

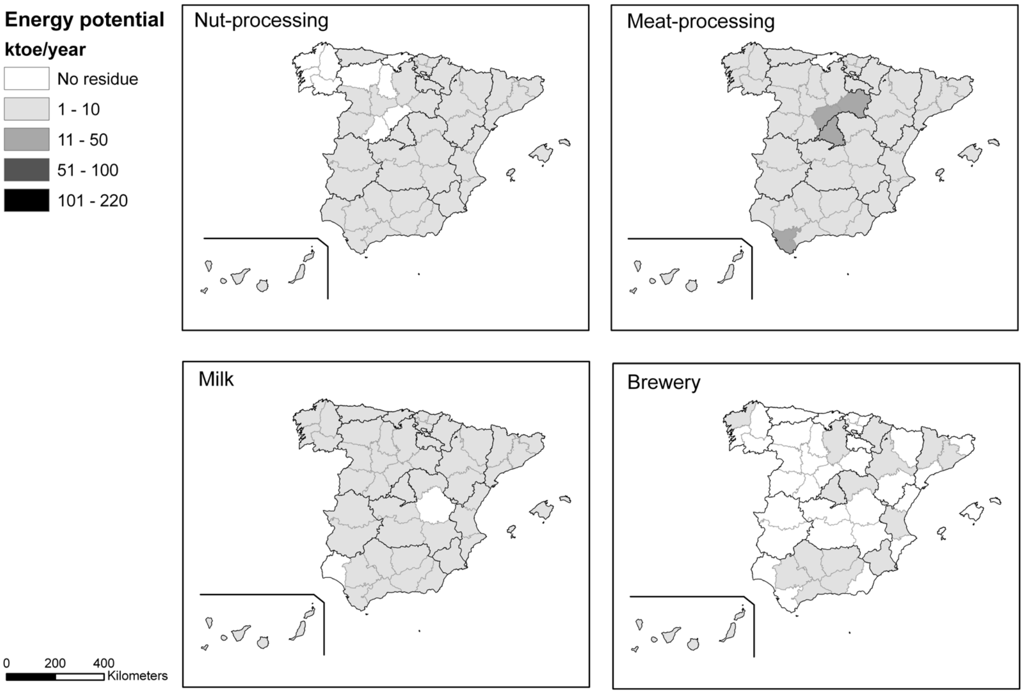


Figure 4: Geographic distribution of the energy potential of nut-processing, meat-processing, wood-processing, dairy plants and brewery residues.

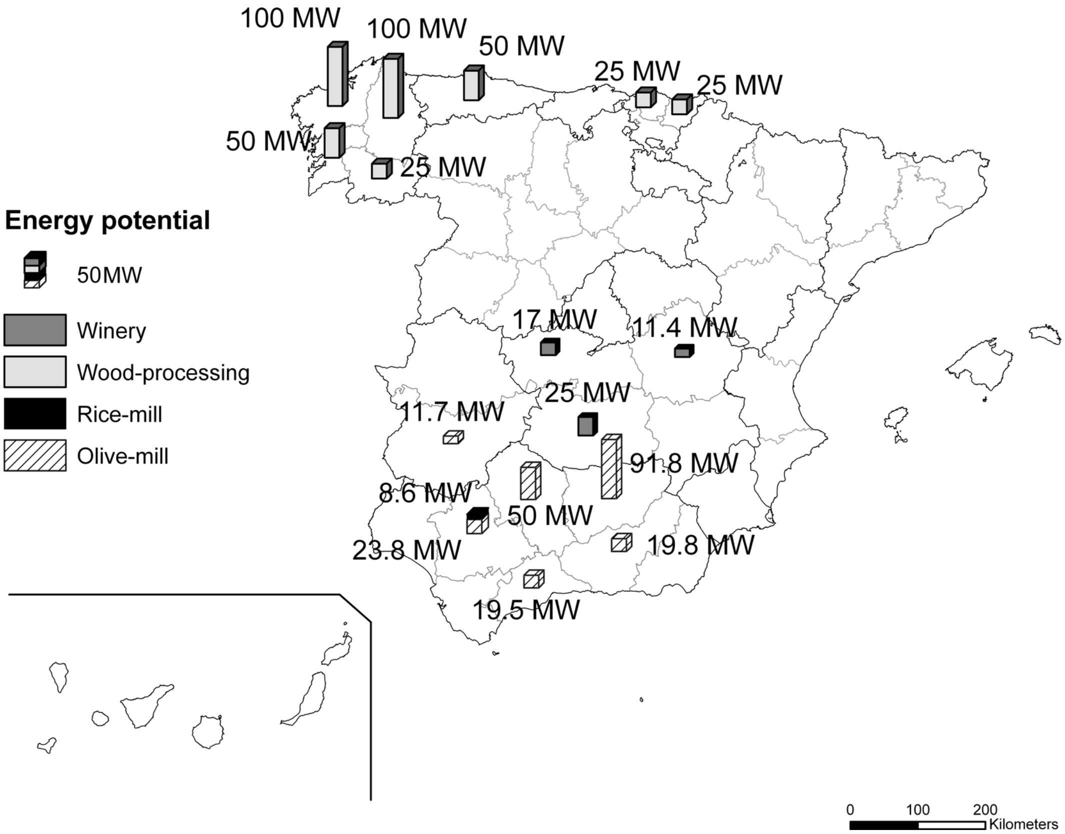


Figure 5: Geographic location of the GF/ST plants with positive net present value.

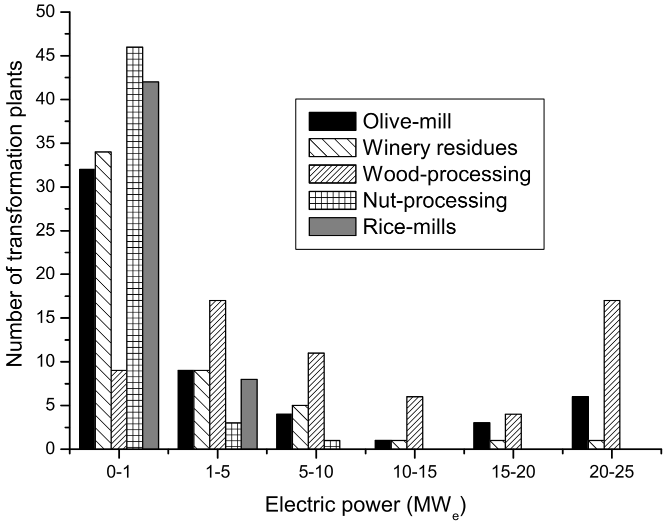


Figure 6: Number of GF/ST plants for different ranges of electric power and for the residues analysed in this work.

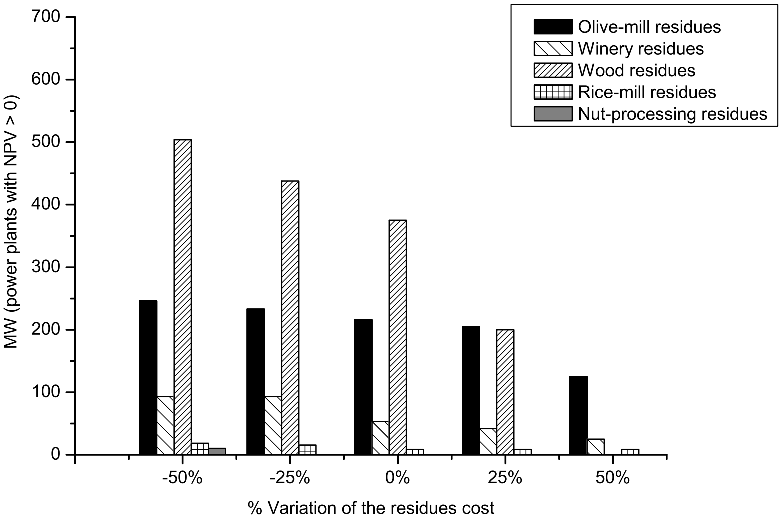
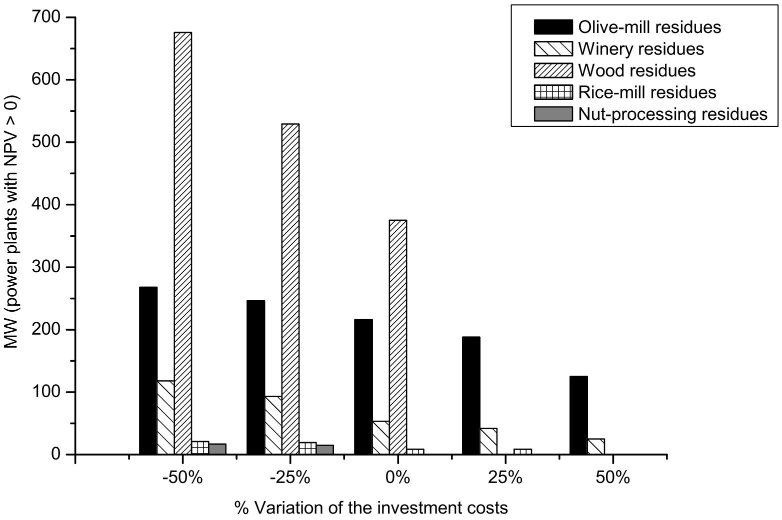


Figure 7: Influence of the residues cost in the profitability of GF/ST plants.



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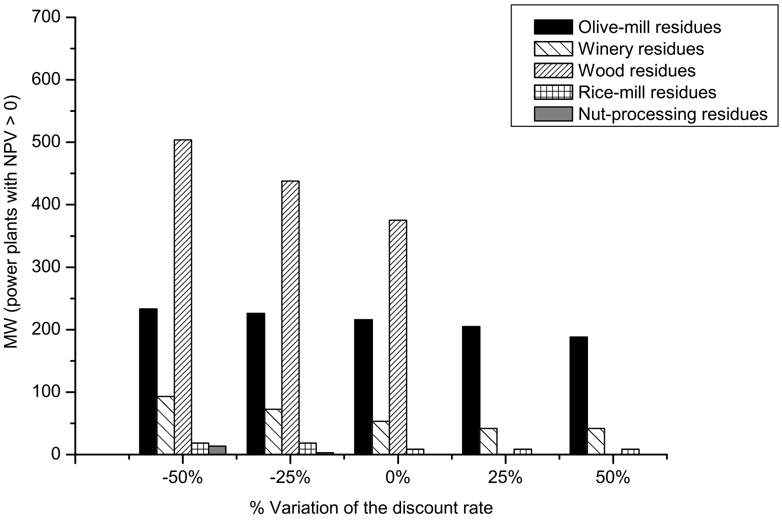

Figure 9: Influence of the discount rate in the profitability of GF/ST plants.

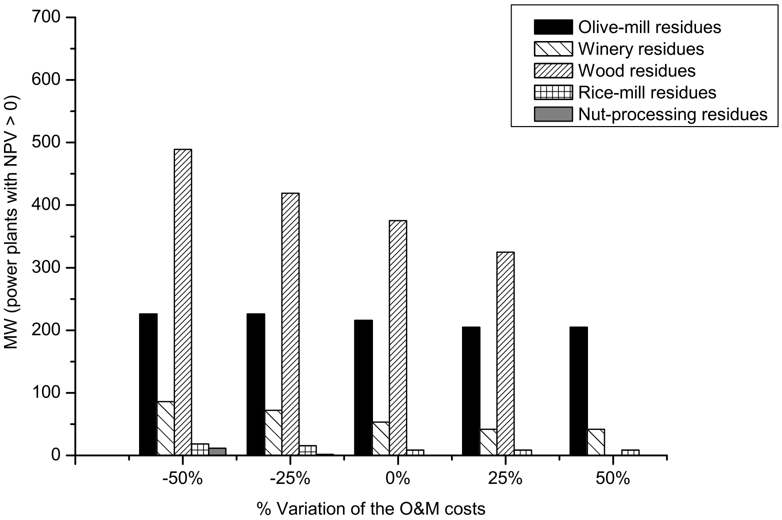

Figure 10: Influence of the O&M cost in the profitability of GF/ST plants.

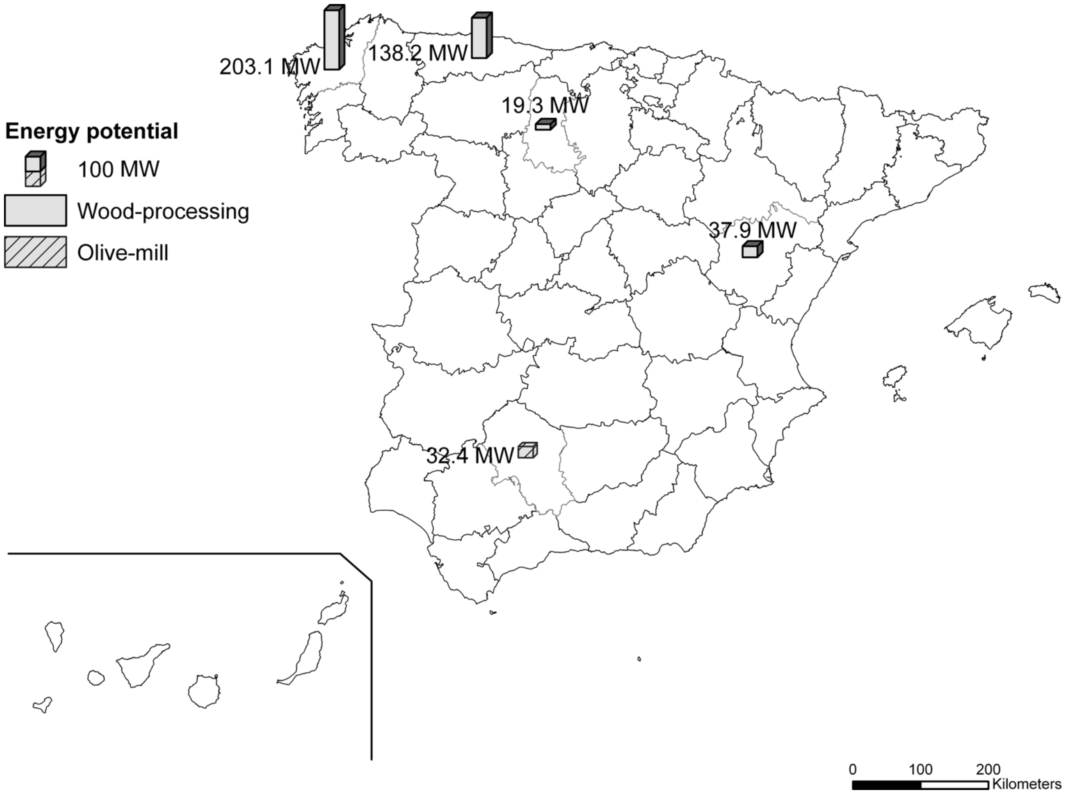

Figure 11: Geographic location of the CF/PC plants with substantial share from agro-industrial residues.

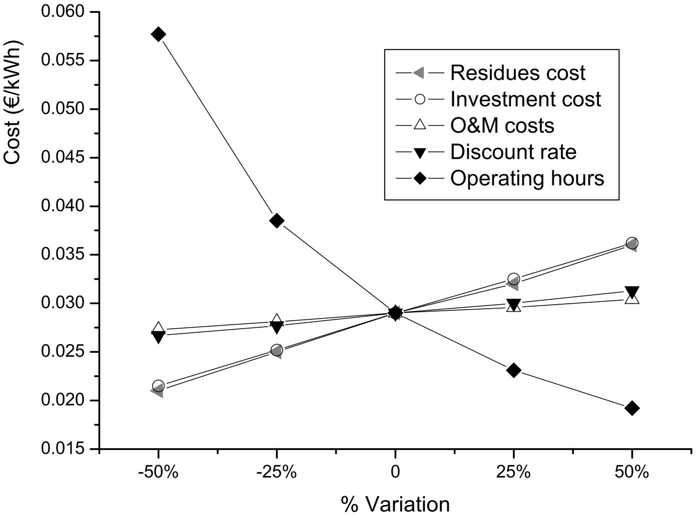

Figure 12: Sensitivity analysis of the electricity cost by co-firing wood-processing residues in coal power plants.

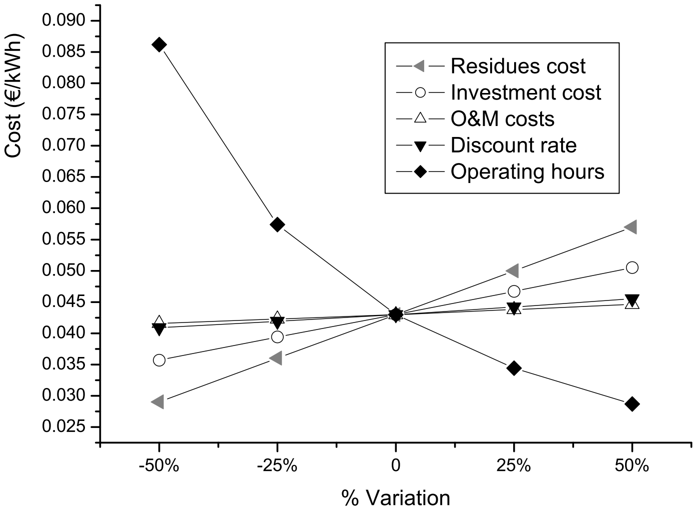

Figure 13: Sensitivity analysis of the electricity cost by co-firing olive-mill residues in coal power plants.

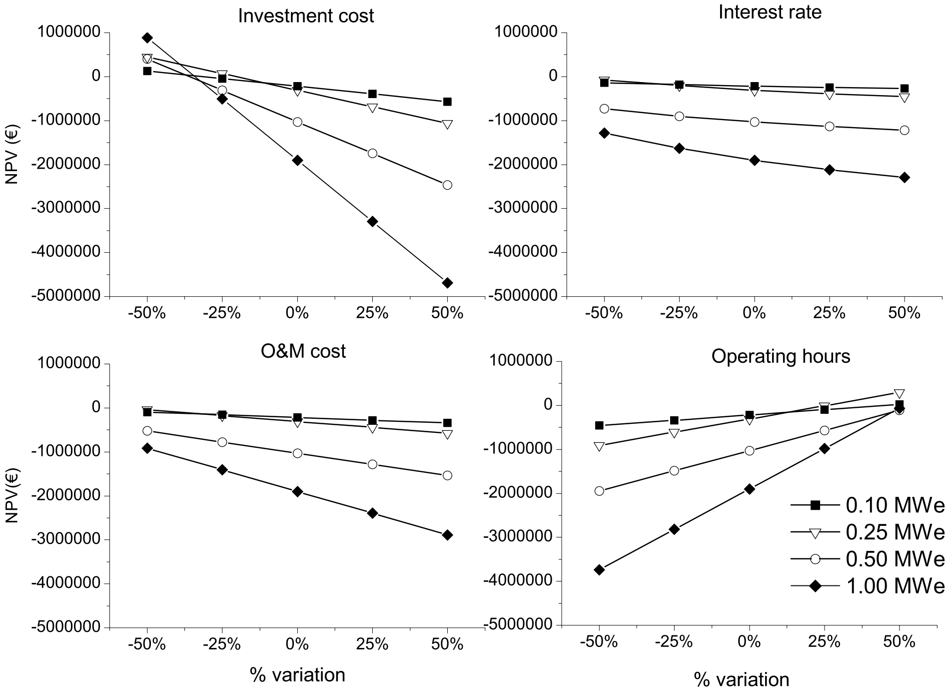

Figure 14: Sensitivity analysis of electricity cost by AD/ICE plants without heat recovery.

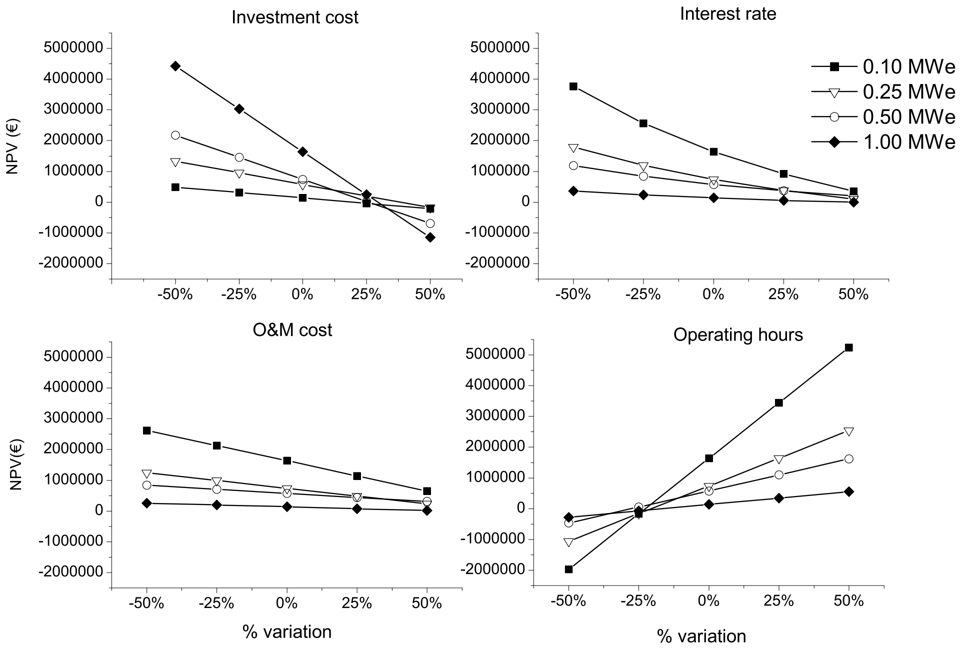

Figure 15: Sensitivity analysis of electricity cost by AD/ICE plants with heat recovery.

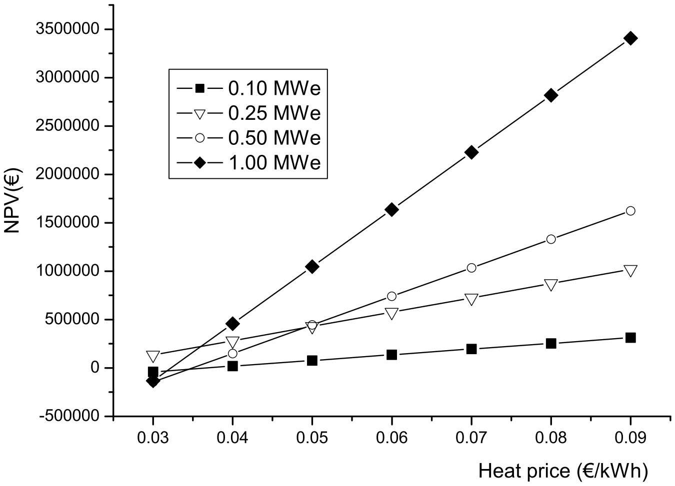

Figure 16: Influence of the heat price in the profitability of AD/ICE plants with heat recovery.

Source of the residue	Residue	Moisture (% w.b.)
Olive mills	olive husk	50
	olive mill wastewater	94
	sludge	65
Wineries	grape pomace	60
Timber and wood processing industries	logging residues	50-55
	bark	25-75
	sawdust	25-40
	shavings	10-20
Nut processing industries	almond husk	3
	hazelnut husk	11.8
Rice mills	rice husk	6
Meat processing industries	wastewater	
Dairies	wastewater	
Breweries	spent grain	≥ 70

Table 1: Typical moisture of the residues studied as produced.

Extraction system	% Penetration	Byproduct	Ratio byproduct/olives (%)
Presses	15	Oil	20
		OH	40
		OMW	40
Three-phase	15	Oil	20
		OH	50
		OMW	120
Two-phase	70	Oil	20
		Sludge	80

Table 2: Fraction (in percentage) of byproducts depending of the extraction technology used in olive mills, and their penetration in the Spanish industry.

Residue	Primary energy *ktoe/year*
Olive mills	579.9
Wineries	282.4
Wood processing	1473.0
Nut processing	50.8
Rice mills	52.8
Meat processing	148.8
Diaries	25.3
Breweries	12.7
Agro-food industries	2625.7

Table 3: Primary energy potential (*ktoe*/year) for the biomass sources analyzed.

	Olive mills *ktoe/year*	Wood processing *ktoe/year*	Nut processing *ktoe/year*	Rice mills *ktoe/year*
This study (Spain)	579.9	1473	50.8	52.8
Siemons et al. (2004)	-	2085	-	-
AFB-NET (2000)	-	2629	-	-
Ericsson and Nilsson (2006)	-	1673	-	-
This study (Andalusia only)	451	68	7	21
Andalusian Energy Agency (2007)	455	41	17	19

Table 4: Energy potential of some of the agro-industrial residues in Spain and Andalusia reported in several studies.

Technology		
GF/ST	Electrical efficiency	$\eta_e = 0.0323\, Ln\,(x) + 0.1545\,(x, MW_{th})$
	Investment cost	$C_{inv}(€/kW_e) = -966.6\ \cdot Ln\,(x) + 5206.7\,(x, MW_e)$
	O&M cost	$OM\ (€/year) = 4\%$ of initial investment
	Operating hours	7000 h
	Lifetime	20 years
	Discount rate	9%
CF/PC	Electrical efficiency	$\eta_e = 0.38$
	Investment cost	$C_{inv}(€/kW_e) = 300$
	O&M cost	$OM\ (€/y) = 4\%$ of initial investment
	Operating hours	4000 h
	Lifetime	10 years
	Discount rate	9%
AD/ICE	Electrical efficiency	$\eta_{AD} = 0.26$
	Heat efficiency	$\eta_{h,AD} = 0.40$
	Investment cost	$C_{inv}(€/kW_e) = 101522/x + 3500\,(x, kW_e)$
	O&M cost	$\alpha = 6\%$ of initial investment
	Heat price	$P_h = 0.06€/kWh$
	Operating hours	4200 h
	Lifetime	20 years
	Discount rate	9%

Table 5: Parameters used for the economic analysis of GF/ST, CF/PC and AD/ICE technologies.

Agro-industrial residues		
Electric Power	Time	c€/kWh
$< 2\ MW_e$	First 15 years	12.5710
	From then onwards	8.4752
$> 2\ MW_e$	First 15 years	10.7540
	From then onwards	8.0660
Wood-processing industry residues		
Electric Power	Time	c€/kWh
$< 2\ MW_e$	First 15 years	9.2800
	From then onwards	6.5100
$> 2\ MW_e$	First 15 years	6.5080
	From then onwards	6.5080
Biogas from biodegradable residues		
Electric Power	Time	c€/kWh
$< 500\ kW_e$	First 15 years	13.069
	From then onwards	6.5100
$> 500\ kW_e$	First 15 years	9.6800
	From then onwards	6.5100

Table 6: Feed-in tariffs for electricity production from agro-industrial residues, wood-processing residues and biogas in Spain (MITYC, 2007b)

Residue	Cost at transformation plant (€/GJ)
Olive-mill	3.0
Winery	3.0
Wood-processing	1.5
Nut-processing	1.5
Rice-mill	1.5

Table 7: Assumed cost of the residues at transformation plant. Transport and drying costs are included.

Province	Power MW_e
A Coruña	2031
Asturias	1628
Almería	1159
Cádiz	568
Córdoba	324
León	1451
Palencia	361
Teruel	366
Total	7888

Table 8: Location and power of coal boilers in Spain by 2020.

Olive-mill residues				
Province	Electric power (MW_e)	Generation (TWh)	NPV (M€)	PI
Badajoz	11.7	0.082	1.14	1.03
Córdoba	50.0	0.35		
	2 plants 25.0 MW_e		33.30	1.64
Granada	19.8	0.139	19.06	1.41
Jaén	91.8	0.525		
	3 plants 25.0 MW_e		33.30	1.64
	1 plant 16.8		11.67	1.28
Malaga	19.5	0.137	18.23	1.40
Sevilla	23.8	0.167	29.91	1.59
Total	216.6	1.516		
Winery residues				
Province	Electric power (MW_e)	Generation (TWh)	NPV (M€)	PI
Ciudad Real	25.00	0.175	37.33	1.71
Cuenca	11.40	0.079	2.96	1.09
Toledo	17.00	0.119	15.13	1.36
Total	53.40	0.373		
Wood-processing residues				
Province	Electric power (MW_e)	Generation (TWh)	NPV (M€)	PI
A Coruña	100.0	0.743		
	4 plants 25.0 MW_e		3.47	1.07
Guipuzcoa	25.0	0.183	3.47	1.07
Lugo	100.0	0.752		
	4 plants 25.0 MW_e		3.47	1.07
Ourense	25.0	0.152	3.47	1.07
Asturias	50.0	0.432		
	2 plants 25.0 MW_e		3.47	1.07
Pontevedra	50.0	0.409		
	2 plants 25.0 MW_e		3.47	1.07
Vizcaya	25.0	0.316	3.47	1.07
Total	375.0	2.625		
Rice-mill residues				
Province	Electric power (MW_e)	Generation (TWh)	NPV (M€)	PI
Sevilla	8.6	0.060	9.62	1.36

Table 9: Location, electric power, electric generation, net present value and profitability index of GF/ST plants with a positive NPV.

Province	Olive-mill	Winery	Wood-processing	Rice-mill	Nut-processing
A Coruña	0.00%	0.06%	11.70 %	0%	0%
Asturias	0.00%	0.00%	8.49 %	0%	0%
Almería	0.70%	0.02%	0.56 %	0.00%	0.32%
Cádiz	0.79%	0.49%	0.34 %	0.29%	0.03%
Córdoba	40.37%	0.75%	1.42 %	0.00%	0.09%
León	0.00%	0.19%	1.46 %	0.00%	0.00%
Palencia	0.00%	0.02%	5.28 %	0.00%	0.00%
Teruel	1.07%	0.12%	6.67 %	0.00%	0.93%

Table 10: Share of agro-industrial residues in coal power plants (considering only residues generated in the same province) whose lifetime will be extended, at least, until 2020.

Province	Coal boilers power	Residue type	Residues share (%)	Co-firing power (MW_e)	Electric generation (TWh)
A Coruña	2031	Wood-processing	10.00 %	203.1	0.812
Asturias	1628	Wood-processing	8.49 %	138.2	0.553
Córdoba	324	Olive-mill	10.00 %	32.4	0.130
Palencia	361	Wood-processing	5.28 %	19.3	0.077
Teruel	366	Wood-processing	6.67 %	37.9	0.152
Total				430.9	1.724

Table 11: Co-firing power and generation considering only coal power plants with substantial shares of agro-industrial residues.

Meat-processing industry wastewater

Size	Electric power	NPV	NPV	PI
ton year^{-1}	MW_e	(only electr.)	(CHP)	(CHP)
25 000	0.387	-408 360	949 831	1.65
50 000	0.775	-1 536 240	1 180 142	1.42
100 000	1.550	-2 915 354	2 517 412	1.46
150 000	2.325	-4 294 467	3 854 682	1.47

Brewery residues

Size	Electric power	NPV	NPV	PI
miles hl year^{-1}	MW_e	(only electr.)	(CHP)	(CHP)
500	0.135	-244 464	227 690	1.40
1 000	0.269	-331 801	612 507	1.59
1 500	0.404	-419 139	997 324	1.66
2 000	0.539	-1 115 982	772 636	1.39

Dairy products wastewater

Size	Electric power	NPV	NPV	PI
ton year^{-1}	MW_e	(only electr.)	(CHP)	(CHP)
25 000	0.160	-260 632	205 668	1.45
50 000	0.319	-364 138	568 464	1.62
100 000	0.479	-467 644	931 260	1.68
150 000	0.639	-1 293 489	571 716	1.40

Table 12: Electric power and profitability of AD/ICE installations corresponding to different sizes of the generating-residues industries