CODEN STJSAO ISSN 0562-1887
ZX470/1463 UDK 620.95:662.612:662.63:621.311.22

Assessment of Biomass Co-Firing Potentials in Coal Power Plants

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Original scientific paper

This paper presents the methodology and results of a country assessment on the capacity of biomass resources to replace partially the coal used in coal power plants (CPP), commonly known as biomass co-firing. The framework for the exemplification has been the Spanish case. The analysis of the Spanish CPPs in the last decade has included technology characterization and evolution and future foresights of electricity production. A total of 20 CPPs consisting of 39 operational coal power units (CPU) using pulverized fuel (PF) systems have been grouped in geographical zones. The available biomass (currently no utilised resources) in 100km area around the CPPs amoutns up to 72.5 PJ y-1. The changes caused by the differences of biomass as fuel have been reviewed, showing that using co-firing rates in the CPUs up to 10% in energy has shown to keep PF units under safe operation. Technical limitations have cut the biomass potential down to 36.5 PJ y-1, equivalent to a 5.4% co-firing rate. This figure is equivalent to a duplication of the current biomass installed power in Spain and to a contribution to the gap of the biomass national objectives of 67%. Economic analysis suggests that co-firing could be economically feasible by providing a bonus between 0.19 and 0.72 €cent per MJ of electricity, which turns into one sixth of the current bonus applied in Spain for electricity produced in biomass power plants.

Keywords
Biomass resources
Coal combustion
Co-fring
Feasibility assessment
Power generation

Procjena potencijala za suspaljivanje biomase u elektranama na ugljen

Izvornoznanstveni članak

Ključne riječi
Izvori biomase
Izgaranje ugljena
Procjena izvodljivosti
Proizvodnja električne energije
Suspaljivanje

Received (primljeno): 2009-11-27
Accepted (prihvaćeno): 2010-05-12

1. Introduction

The reduction of greenhouse gas (GHG) emissions is currently the centre of attention of the energy and environment policies implemented in most European countries. Actions are demanded with urgency in Europe under acknowledgement of the impacts of GHG emissions in the climate change and the need for efficient policies counterbacking its effect (see the European parliament resolution [1] and the European Commission proposals [2] and [3]). As it was reported by the European Commission [3], energy accounts for 80% of all GHG emissions in the EU (European Union). One of the GHG reduction lines promoted in the EU is the stimulation of the use of renewable energy sources, for example biomass for heat and power production as well as for production of biofuels for transportation [4]. In concrete co-firing, that is, the partial substitution of consumed solid fossil fuel by solid biomass is a direct alternative leading to a net reduction in GHG emissions.

Biomass co-firing is one of the most effective means of reducing GHG emissions in coal power plants (CPP) assuming its neutral role in the CO_2 balance according to reference studies (e.g. [4-6]); the neutral role of the biomass is actually dependent on the energy and resources invested in its procurement. Along with it, co-firing

Symbols/Oznake

A - area, ha
- površina

AN - anthracite coal type
- antracit

AEP - average energy production for the period 1998-2007, PJ
- prosječna proizvodnja energije za razdoblje 1998- 2007

AI - availability index, percentage of biomass expected to be available with respect tothe total potential resources, %
- indeks dostupnosti, postotak biomase koja se očekuje da će biti dostupna u odnosu na ukupne moguće izvore

ARB - agricultural residual biomass
- poljoprivredna biomasa

B - bituminous coal type
- bitumenski ugljen

BL - brown lignite coal type
- smeđi lignit

CC - correlation coefficient
- korelacijski koeficijent

CFB - circulating fluidized bed
- cirkulirajući fluidizirani sloj

Cl - chlorine
- klor

CO_2 - carbon dioxide
- ugljični dioksid

CPP - coal power plant, a plant may consist of various power units
- elektrana na ugljen, moze imati različite blokove

CPU - coal power unit, a thermoelectric group consisting of a boiler and a coupled steam turbine
- blok elektrane, sastoji se od generatora pare i parne turbine

CV - coefficient of variation, as the percentage of the standard deviation with respect to the mean, %
- koeficijent varijacije, kao postotak standardne devijacije u odnosu na srednju vrijednost

DS - down-shot firing system
- sustav izgaranja s gorionicima koji gledaju prema dolje

EEP - expected energy production calculated by moderating the average energy production (AEP) with the coefficient of variation (CV), PJ
- očekivana proizvodnja energije dobivena množenjem prosječne proizvodnje energije (AEP) s koeficijentom varijacije (CV)

ESP - electrostatic precipitator
- elektrostatski filter

EU - European Union
- Europska Unija

F - front-wall fired system
- sustav izgaranja na prednjem zidu

FB - fluidised bed
- fluidizirani sloj

FGD - flue gas desulfuration
- odsumporavanje dimnih plinova

FRB - forest residual biomass, PJ
- šumska biomasa

GHG - greenhouse gases
- staklenički plinovi

GCDB - Global Co-firing Database
- svjetska baza podataka o suspaljivanju

GIS - geographical information system
- geografski informacijski sustav

H - horizontal firing system
- horizontalni sustav paljenja

HARB - herbaceous agricultural residual biomass
- poljoprivredna biomasa

HP - hydro power
- hidro elektrane

I - imported coal
- uvezeni ugljen

IGCC - Integrated Gasification Combined Cycle
- kombinirani ciklus integriranog uplinjavanja

IP - installed power, MW
- instalirana snaga

IZ - influence zone
- zona utjecaja

LHV - lower heating value expressed in wet basis, $kJ\ kg^{-1}$
- donja ogrijevna vrijednost

M - biomass production, $kg\ y^{-1}$
- proizvodnja biomase

N - national coal
- domaći ugljen

NO_x - nitrogen oxides
- dušikovi oksidi

Nr - number of the CPU into the CPP
- broj CPU u CPP

NUT - nomenclature of territorial Units for Statistics, used by EUROSTAT for statistics with the regulation (EC) No 1059/2003
- nomenklatura teritorijanih Jedinica za Statistiku, upotrebljavana od strane EUROSTAT-a za statistike s uredbom (EC) No 1059/2003

O&M - operation and maintenance
- vođenje i održavanje

PA - proximity area; PA40, PA60, PA80 and PA100 denote the distance to power plants of 40, 60, 80 and 100 km respectively
- blizina površina; PA 40, PA60, PA80 i PA 100 označava udaljenost električnih postrojenja od 40, 60, 80 i 100 km

PCFB - pressurized circulating fluidized bed
- cirkulirajući fluidizirani sloj pod tlakom

PF - pulverised fuel
- prašinasto gorivo

PT	- production types, which is as next: PT1 for base demand plants; PT2 for plants which production depends on annual hydro power; PT3 for plants with irregular production - proizvodni tipovi, koji su kako slijedi: PT1 za bazna postrojenja; PT2 za postrojenja čija proizvodnja ovisi o godišnjoj proizvodnji hidro elektrana; PT3 za postrojenja s neredovitom proizvodnjom
RPR	- residue to product ratio, kilograms of biomass obtained by kilogram of product, kg kg^{-1} - odnos ostatka prema proizvodnji, kilogrami biomase dobiveni po kilogramu produkta
RSR	- residue to surface ratio, kg ha^{-1} y^{-1} - omjer ostatka prema površini
SB	- subituminous coal type - sub-bitumenski ugljen
SCR	- selective catalytic reduction - selektivna katalitička redukcija
SO_2	- sulphur dioxide - sumporni dioksid
T	- tangential fired system - tangencijalni sustav izgaranja
w	- moisture content as percentage on a wet basis - sadržaj vlage kao postotak na vlažnoj osnovi
WARB	- woody agricultural residual biomass - šumska biomasa
Y	- product yield of a crop, kg $ha^{-1}y^{-1}$ - prinos usjeva
η	- Electrical efficiency of coal power unit - Električna efikasnost elektrane na ugljen

Indices/Indeksi

b	- biomass - biomasa
e	- electricity - električna energija
P	- product of an agricultural crop - poljoprivredni proizvod
th	- thermal - toplinski

shall be regarded as an opportunity for fuel dependence reduction, employment creation and promotion of rural development in regard to the cost-efficient lignocellulosic feedstocks with respect to conventional European agricultural crops in the long term [7].

According to EUROSTAT [8] the EU27 based up to 30 % of its electricity production on coal during 2006. Potentials of co-firing in the EU27 have been proposed to range from 5.2 to 9.3 % according to large-scale assessment based on main relevant country figures that assumed a maximum co-firing energy rate of 10 % in Pulverised Fuel (PF) plants and of 20 % in Fluidised Bed (FB) plants [9].

When focusing on particular countries, it is observed than 15 out the 27 European Member States produce more than 20 % of their electricity with coal. Other European non member countries present as well important shares of coal in the electricity balance like Turkey with 30 % and Croatia with almost 20 %. The question arises there: how high is the potential for biomass co-firing in a country and how to carry out an assessment of its feasibility?.

The precise determination of co-firing potentials at country level provides a first hint in the potential reduction of GHG emissions by means of biomass use in CPPs. The case of Spain (which accounts for the fourth largest coal installed power among the EU27 [8]) is analysed in the present paper applying a holistic analysis accounting sector configuration, biomass resources and prices, technical limitations for co-firing and economics. The analysis is exemplified for the Spanish sector, which accounts for an important coal based installed power (IP).

As a first step, a coal power-park is characterized by CPP according to current and future expected power production regime, combustion technology and geographical location. Secondly, potential and available biomass (agricultural and forestry resources) are assessed in 100 km radius around the CPPs using data from Spanish inventories. Thirdly, the maximum biomass co-firing rate for a secure and non problematic operation according to the state of the art and the combustion technologies used in the CPPs is revised. Fourthly, comparison of available biomass resources by CPPs with maximum percentage for co-firing results provides the current potential of co-firing in Spain. In the fifth place the paper exposes an economic profitability analysis that accounts for market biomass prices, technology costs and emissions trade in order to observe the current viability of co-firing in Spain.

2. Coal power production: sector analysis

Biomass co-firing in CPPs involves the combustion of biomass as an alternative fuel together with coal in combustion facilities originally designed for coal combustion. Combustion characteristics of coal and biomass differ to a certain extent as regards their different content on volatile matter and fixed carbon, energy density, moisture and inorganic material composition. Along with fuel characteristics, the boiler technology and the plant configuration (milling and feeding system, capacity of gas circuit, type of boiler operation, etc) are fundamental for determining the best co-firing system per facility. At this moment there are 20 CPPs participating in the Spanish electricity market; these CPPs in some cases include several coal power units (CPUs) with different nominal power, technology and even type of coal. A detailed characterization of the particular characteristics for the complete CPUs in Spain is an enormous task. Therefore, for the present country analysis, CPUs have been characterized adequately to the scope, accounting for the necessary information to evaluate major factors limiting co-firing [10]. Combustion technology and coal, total CPU installed power and their production have been used to roughly determine the flexibility and capacity of a CPP to cope with the difficulties caused by the multifuel combustion. Production regime, age and current status serves for short term prediction of the expected production and life time of the facility.

Characterization of the Spanish CPUs is based on an extensive data collection supported by the large expertise of CIRCE with the Spanish power sector. Technology description and fuel consumption is based on technology reports describing original equipment [11] and updated with data of the IEA Coal Power Database (cited by [12]) and by surveys carried out by CIRCE in 2003 and 2007. Evolution of group power and energy production has been characterized by means of data published in official yearbooks on the Spanish power network for the period 1995-2007 [13]. Plant sitting has been carried out by means of geographical information systems (GIS), required to carry out in a proper way the biomass assessment. Figure 1 depicts CPPs distribution in Spain and their respective influence zones (IZ) in the territory employed for the biomass assessment. An IZ is the territory in which a certain number of CPPs, grouped by proximity among other factors, would obtain the biomass resources for co-firing implementation. This surface is obtained by adding 100 km radius around every CPP included in each zone.

The final result is a detailed database of the Spanish CPPs whose relevant data is presented in Table 1. A total of 20 CPPs including 39 CPUs were active by end of 2007; 38 of them used pulverized fuel (PF) technologies and the remaining CPU consisted of an Integrated Gasification Combined Cycle (IGCC Elcogás in IZ7). La Pereda CPP is a circulating fluidized bed (CFB) sited in IZ2 with 50 MW of installed capacity whose production regime and sales are not facilitated in Spanish power production statistics. Recently the 80 MW pressurized circulating fluidized bed (PCFB) coal combustor unit in Escatrón CPP shut down. Because of the respective reasons discussed above, both La Pereda and Escatrón CPPs have been excluded from analysis.

A production regime under liberalized legal framework started in Spain in 1998. Annual CPUs production and technical availability [13] has been analysed for the period 1998-2007. Power demand in Spain is basically covered by thermal (nuclear, coal and recently increasing gas combined cycles) and hydro power. Hydro power (HP) production varies to a large extent for years in Spain due to the significant variation on reservoirs water reserves caused by the irregular rainfalls of the Mediterranean climate. Whereas nuclear plant production is constant and independent of other factors than technical stops, an inverse inter-annual relation of coal (CPPs) production to hydropower (HP) production has been observed. Statistical analysis on CPP versus HP production data series (1998-2007) revealed a discrete correlation coefficient (CC=-0.46) for the total produced energy in Spain.

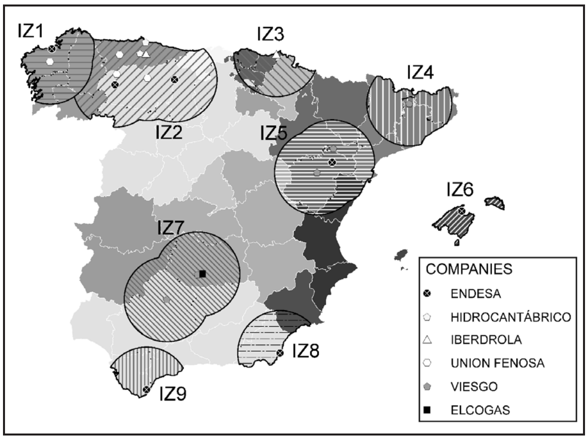

Figure 1. Map of the Spanish Coal Power Plants (CPP) and their influence zones (IZ) depicted with a 100 km radius circle

Slika 1. Lokacije španjolskih elektrana na ugljen (CPP) i njihove zone utjecaja (IZ), prikazane krugovima radijusa 100 km

Production series of each singular CPU have been additionally analysed. Firstly, annual production has been corrected according to the CPU technical availability (percentage of hours that the CPU undergoes maintenance or upgrading operations). In this way the percentage, of actual production with respect to maximum attainable production (full load production during time of technical availability) has been obtained. By observing the evolution of these percentages three production types (PT) have been differenciated: CPUs covering base demand (PT1) whose production only depends on CPU technical availability; CPUs which production is inversely correlated to annual HP (PT2); and finally, CPUs whose irregular production (PT3). When observing the coefficient of variation (CV) in the production time series it has been observed that CVs served to classify CPUs by PT: as next: CV_{PT1} from 0 to 10 %; CV_{PT2} from 10 to 20 %; CV_{PT3} over 20 %.

The estimation of the energy produced yearly by a CPU under normal operation is an important input parameter to calculate which percentage of coal energy can be replaced by the available biomass resources. By comparing this percentage with the maximum biomass co-firing rate preserving the CPUs from operational problems, it is estimated if the whole biomass can be used or if only part of the resources can be co-fired.

As regards the variability of the annual energy production of the CPUs, especially those described as PT2 and PT3, the use of the Average Energy Production (AEP) of a number of years may result in slightly optimistic predictions. This is specially true for years with low load factors, for whom the same amount of biomass implies larger energy shares with respect to the used coal, that is a larger co-firing rate.

Aiming at determining a reasonable figure for the energy production by CPU that can be produced in the near future the Expected Energy Production (EEP) has been calculated. The EEP discounts from the average energy production (AEP) of a series of years a percentage that corresponds to the CPU specific coefficient of variation (CV). The subtraction of the CV proportional from the AEP has been used aiming at obtaining a conservative prediction of the energy produced. EPPs calculated by CPU can be summed up by CPP and by IZ as shown in equation (1).

$$EEP_{IZ} = \sum_{IZ=1}^{9} \left(\sum_{CPU=1}^{n} \frac{(100 - CV_{CPU}) \cdot AEP_{CPU}}{100} \right). \qquad (1)$$

As can be observed in Table 1, Spanish CPPs park is quite varied as it includes very old to new modern power stations. Two groups (additional to Escatrón, as explained above) shut down in 2007 and four groups have a transitory lifetime until 2015 in compliance with large combustion plant directive (LCP Directive 2001/80/CE), which requires the combustion facilities either to adapt their pollutant emissions to the directive or to program the shut-down of the facility by 2015. Meanwhile their transitory maximum production is up to 20,000 equivalent hours since 2008. These groups, though they will work under a transitory regime, are available for co-firing in the medium term.

The medium term prediction of both the Spanish Association of Power Companies (UNESA) [14] and the Spanish Ministry of Industry, Tourism and Trade [15] coincide that CPPs will operate with a gradual annual decay (around 3 %) leading to a total decrease of 30% in the next decade. In the short term productions lower than the average (AEP) are expected, and for this reason in the short term the use of the slightly conservative EEP is more recommended, at least until the negative foresights take place. In the long term, beyond 2015, CPUs will enter the end of their useful life period. Retrofitting to new clean coal technologies may enlarge their lifetime 15 extra years; the persistence of coal with a significant role in the Spanish electricity mix share is not expected unless new supercritical efficient coal technologies with CO_2 capture will be installed (perspectives of the sector in [14-15].

3. Biomass availability

Reference studies analysing national [16] or European [9] co-firing potentials do not always include as starting point the biomass potential determination. In large scale studies it is complex to integrate biomass assessments with international biomass trade options or with technical, economical or political issues on co-firing. Berggren and co-workers [17] proposed an analysis of the national biomass resources for co-firing in Poland by using a NUTs2 [18] resolution.

Biomass assessment in the present work involves the study of a large portion of the Spanish territory. NUTs3 geographical resolution (Spanish provinces) has been selected to provide sufficient zonal accuracy for the assessment of local biomass resources around the consumption centres (IZ). Permeability of frontiers to biomass trade (exemplified in other works [9]) has been neglected; thus co-firing potentials are based only on national resources. Forestry and agricultural resources are the primary biomass resources capable of being used in the short term. Energy crops are still not cultivated in Spain as source for lignocellulose for energy producers, and therefore they have been excluded from the assessment.

The selected methodologies for agricultural and forest biomass used have been based on knowledge acquired during the Spanish National R&D Project ENE2005-00304 (details of final results available in [10] and details of methodology in [19]). Though methodologies have been developed to an advanced state-of-the art including high geographical resolution (land use coverages), use of complex algorithms for forestry biomass assessment and technical availability, regressions for biomass and determination of reliability of biomass assessment by means of statistical work, the approach used for the country analysis has based on an easier scale appropriate for an analysis in such huge area as the Spanish territory.

The biomass assessment used in the present study is based on ratios that correlate figures like the area or the yield of a particular zone with its biomass production. Use of ratios is a widespread methodology for biomass assessments, appropriate for both large and small scale. Adequate ratios for Mediterranean areas have been compiled from a large series of studies, from reference [20] to reference [30].

Such ratios are usually named as Residue to Surface Ratio (RSR) when correlating biomass production to planted area (expressed by kg of biomass per ha) and Residue to Product Ratio (RPR) when correlating biomass fraction to product fraction of the plant (for example kg of biomass per kg of grain). To assess the biomass resources equation (2) and equation (3) are used.

$$\mathrm{M_b}[\mathrm{kg\ y^{-1}}] = A[\mathrm{ha\ y^{-1}}]\, RSR\ [\mathrm{kg_b\ ha^{-1}}], \qquad (2)$$

$$M_b[\text{kg y}^{-1}] = A[\text{ha y}^{-1}]\, Y[\text{kg}_p\ \text{ha}^{-1}]\, \text{RPR}[\text{kg}_b \text{kg}_p^{-1}]. \quad (3)$$

Equations (2) and (3) use as input either only area (A), or both, area (A) and yield (Y). Area is a variable easily found in agricultural or forestry inventories. Yield of crops is usually also available, though in general only provided as average of large areas (like regions or provinces). In case of forestry inventories the amount of timber volume per hectare is often utilized to describe forestry masses, though forestry residues (branches, tree tops) are not described.

Table 1. Spanish coal power plants (CPP) and coal power units (CPU) arranged by influence zone (IZ) and characterised by: coal type and average annual consumption, percentage of carbon dioxide credit emissions covered, technology, age of commissioning, installed power (IP) average production (AEP) and production type (PT), and power and expected energy production (EEP) in the short term

Tablica 1. Prikaz španjolskih elektrana na ugljen (CPP) i blokova elektrana (CPU) poredanih prema zoni utjecaja (IZ) i podacima o: vrsti ugljena, prosječnoj godišnjoj potrošnji, udjelu pokrivenosti kvota emisija ugljičnog dioksida, tehnologiji, godini puštanja u pogon, instaliranoj snazi (IP) prosječnoj godišnjoj proizvodnji (AEP), tipu proizvodnje (PT), snazi i očekivanoj proizvodnji energije (EEP) u kratkom roku

	CPPs				CPUs						EEP	
IZ	CPP	Coal type	Coal [Mt]	$\%_{CO2}$	Nr	Tch	Year	IP [MW]	AEP [PJ]	PT	IP [MW]	EEP [PJ]
1	As Pontes	SB (I)	8.88	79	I	T	1976	369	9.4	1	1468	35.2
					II	T	1977	366	9.1	1		
					III	T	1978	366	9.4	1		
					IV	T	1979	367	8.9	1		
	Meirama	BL,B(N/I)	3.66	58	I	T	1980	563	12.4	2	563	10.9
2	Compostilla	AN,B (N/I)	3.51	72	I	DS	1961	Shut down 2007			1171	24.6
					II	DS	1965	141	2.6	2		
					III	DS	1973	330	7.7	1		
					IV	DS	1984	350	8.3	1		
					V	DS	1984	350	8.3	1		
	Aboño	B (N/I)	2.1	54	I	H	1974	360	8.6	1	916	21.8
					II	H	1985	556	14.5	1		
	Soto de Ribera	B (N/I)	2.02	81	I	DS	1962	Shut down 2007			604	11.2
					II	T	1967	254	4.9	1		
					III	T	1984	350	7.8	2		
	Lada	B(N/I)	0.97	60	III	F	1967	155	1.9	3	505	6.3
					IV	F	1981	358	6.5	3		
	Guardo	AN,B (N/I)	0.98	80	I	DS	1964	155	2.4	3	516	7.5
					II	DS	1984	361	7.2	3		
	La Robla	AN,B (N)	1.68	79	I	DS	1971	284	5.7	2	655	12.7
					II	DS	1984	371	8.4	1		
	Anllares	AN,B (N)	1.15	78	I	DS	1982	365	8.9	2	365	8.0
	Nárcea	AN,B (N)	1.33	80	I	DS	1965§	65	0,4	3	595	10.8
					II	DS	1969	166	2.8	2		
					III	DS	1984	364	8.7	1		
3	Pasajes	B (I)	0.32	81	I	F	1968	217	3.9	3	217	2.9
4	Cercs	SB,B (N/I)	0.43	44	I	H	1971	160	2.8	3	160	2.0
5	Escucha	SB,B (N/I)	0.39	67	I	H	1975	160	2.9	3	160	2.2
	Teruel	SB,B (N/I)	4.37	68	I	H	1979	368	8.1	2	1102	20.2
					II	H	1980	368	8.0	2		
					III	H	1980	366	7.9	2		
6	Alcudia	B (N/I)	0.68	101	I,II	T	1982	125x2	11.2	1	510	10.7
					III,IV	T	1997	130x2		1		
7	Elcogás	B (N)	0.5	NA	I	GICC	1997	320	4.8	1	320	4.4
	Puertollano	B (N)	0.61	79	I	T	1972	221	3.9	2	221	3.3
	Puente Nuevo	AN,B (N)	1.1	76	I	DS	1980	324	7.1	2	324	6.1
8	Los Barrios	B (I)	1.49	85	I	T	1985	568	13.0	1	568	12.3
9	Litoral	B (I)	2.72	80	I	T	1984	577	12.8	1	1144	23.6
					II	T	1996	582	12.6	1		

Usually either a single year value or an average value (of a series of years) is utilized to determine biomass in equations (2) and (3). The utilization of average values leads, however, to significant uncertainties in the biomass assessments [31]. This practice still provides useful results for large scale assessments, but must not be used for plant sitting (either for company strategies or as input for linear optimization procedures) or for the organization of biomass procurement. Additionally biomass assessments based on RPR and RSR provides only a figure on the biomass that is generated annually in a certain area, which is usually referred to as potential biomass resources.

The methodology used here brings a step forward in the country analysis by including the competitiveness for biomass resources, which indeed remediates the overestimation of resources. Results are therefore more reliable for assessment of current co-firing potentials and best sector and company strategies.

3.1. Agricultural residual biomass (ARB)

Agricultural biomass resources accounted for in the present study are the by-products produced from crop management operations carried out year after year, here referred to as agricultural residual biomass (ARB). Two sources have been considered, residual biomass from woody residues (leftover after pruning operations from perennial crops) denominated as WARB, and herbaceous biomass (straw or cane harvested in annual crops) named as HARB.

Biomass has been estimated according to equation (2) for WARB and by equation (3) for HARB. Data on areas (NUTs3) and on agricultural yields has been collected respectively from agricultural inventories [32] and agricultural surveys [33] corresponding to a five year period (2000 – 2004). Input data consisted of 5 year average data on areas and yields along with average RPR and RSR ratios (Table 2) obtained from ratios representative for Mediterranean areas [20-30].

Even when the use of RPR is recommended with respect to RSR [31], RSR have been used for WARB at the large scale impelled by the data scarcity on RPRs for woody crops. Biomass energy content has been calculated by means of the use of a general Lower Heating Value (LHV) for crop groups as next with regard to the values provided by cited literature. LHV and moisture selected were 10,450 kJ kg^{-1} for woody residues at 35 % moisture (w), 13,376 kJ kg^{-1} for straw (w=15 %) and 12,540 kJ kg^{-1} for summer cereals cane (w=20 %). Moisture content was always considered on a wet basis.

From potential biomass obtained at NUTs3 scale, the available biomass can be obtained by means of applying availability indexes (AI). AI implementation must account for current biomass consumed by the sectors producing the biomass (use of biomass for mulching, compost, cattle feedstock, etc) and by the industries currently consuming it or that could participate in the demand in the future. Availability, defined as the percentage of resources still not in use, has been assessed by means of surveys to local producers accounting for more than 100 contacts in 10 of the 50 Spanish provinces. Single AI ranged widely between geographical areas for the same residue. It was found that in certain areas no resources were available, which must prevent use of general AI for studies at local scales. An average AI value was selected by crop type for the 40 provinces (NUTs3) intersecting the 100 km IZs, though for a better geographical accuracy (necessary for downscaling) a complete surveying work in the 40 provinces would have been required. Considering surveyed woody crops AI, the average availability index for these resources reached 90.7 %. Herbaceous biomass AI has been obtained as weighted average of rice straw, winter cereal straw and summer cereal cane availabilities resulting in a 13.4 % AI index. AIs reproduce the present time of biomass market: woody residues are almost not used in Spain whereas cereal straw mainly has a relevant demand. AIs as well serve for estimating the type of procurement risks. While HARB has already a price and a market that may involve future price rises, in the case of WARB the risk arises from the absence of providers and the uncertainty of the price.

3.2. Forestry residual biomass (FRB)

FRB accounts for the non-commercial fraction (branches, tree tops, and non commercial stems) of the forestry biomass obtained in forestry silvicultural operations (forest thinning, regeneration cuts, construction of roads and firebreak openings). Forestry mases are site specific as result of local terrain and micro-climate conditions, types of species and configuration and age of the stories and therefore there are multiple variants in the type of silvicultural treatments, degree of mechanization and frequency . Use of constant RSR per species entails the incorporation of high variability when assessing the FRB [34]. Operations are planned and executed during the life-cycle of the forest, and therefore RSRs for forestry mass represent the average annual production that could be obtained when considering all treatments to be carried out in the whole life cycle. In the present study, a general assessment of FRB has been carried out for Spain, aiming at simply obtaining basic figures in order to roughly foreseen forestry potentials for co-firing at national scale.

RSR for coniferous (*Pinus Sp.) and* deciduous (*Quercus, Fagus and Populus*) have been obtained from data either calculated or selected by Pascual [34]. Eucalyptus RSR relies on indexes provided by a reference Spanish industry network [35]. RSRs obtained in bibliography have been expressed as fresh biomass (w=50 %) as described in Table 2. Spanish forestry statistics yearbook on 2005 [36] has provided by NUTs3 data on area of forest surfaces describing percentages of primary, secondary and tertiary species in the forest masses. FRB has been estimated per forest spot by applying equation (2) and by using specific species RSR multiplied by the corresponding occupied area (forest area multiplied by percentage of occupation). Obtained FRB of the very diverse types of forest mass has been summed up arranged into three main classes: coniferous, deciduous and mixed forests.

Spain is the seventh largest producer of roundwood in the EU27 [37] but however, only a reduced part of the forestry area is planned for production management. Considering only the available FRB from forestry areas with a forest management planning, AI would be limited to 13.8 % [36]. There is, however a large area potentially valid for forest production or to be used for biomass procurement under a sustainable management. In order to bring about a hint on the exploitable forest mass diverse research works (references [34, 38-40]) have defined a technical availability of FRB by classifying forest areas according to the technical limitations for undergoing forestry operations: slope, distance to forest track, extension of the mass area and amount of collectable biomass. An average technical availability of 24 % was obtained for Aragón region (NUTs2 in Spain) [34]; similar work [38] carried out for Aragon by NUTs4 and NUTs2 lead to availabilities of 25 % to 34 % respectively. An availability index (AI) of 30 % has been selected as a general index for Spain. Under this technical criteria available FRB is larger than currently could be obtained from the areas inventoried for exploitation, which actually only represent 13.8 % of the forests area. The value selected for AI is more representative of the resources available for energy production, assuming that in the very near future biomass resources will be exploited not only for roundwood, but for energy.

3.3. Assessment of resources by IZ

In order to attain enough geographical accuracy in the determination of available resources in the proximity of the consumption centres (IZ), agricultural and forestry land coverages from Corine LandCover [41] have been used. Disaggregation of land use types provided by Corine is shown in Table 3 (left side). As observed in Table 3 (left) there are two land use types 211 and 212 for the representation of geographical distribution of herbaceous non permanent crops. Both coverages have been unified by means of GIS operation in order to represent the total non permanent crops, that is, area of winter and summer cereals (rice excluded). As can be observed in the rest of the table, Corine land types (left) correspond with the biomass subtypes (right) calculated by means of the proposed RSRs and RPRs (Table 2).

Biomass per crop type has been calculated by NUTs3. In order to determine the amount of resources by proximity to CPPs, proximity areas (PA) representing radius distance from CPPs ranging from 40 to 100 km radius (PA40 and PA100 respectively) have been created into the GIS. Geographical coverages of PAs (by IZ) have been intersected consecutively with land use area (by corine code) in order to determine its relative occupation with respect to total land use type area in the province (NUTs3). In this way total biomass (either potential or available) originally estimated by NUTs3 in the database is multiplied by each set of occupation indexes (per IZ and per PA) in order to obtain the biomass resources by proximity to IZ.

Table 2. Summary of RSR (kg ha^{-1}y^{-1}) and RPR (kg kg^{-1}y^{-1}) average values used for the assessment of biomass resources: WARB (w=35 %), HARB (w_{straw}=15 %; w_{cane}=20 %) and FRB (w=50 %)

Tablica 2. Prikaz srednjih vrijednosti RSR-a (kg ha-1y-1) i RPR (kg kg-1y-1) korištenih za procjenu potencijala različitih tipova biomase: WARB (w= 35 %), HARB (w_{straw}=15 %; w_{cane}=20 %) i FRB (w=50 %)

AGRICULTURAL RESOURCES / POLJOPRIVREDNA BIOMASA				FORESTRY BIOMASS / ŠUMSKA BIOMASA			
WARB / Drvni ostaci		HARB / Poljoprivredni ostaci		CONIFEROUS / ČETINARI		DECIDUOUS / BJELOGORICA	
Crop / Usjev	RSR	Crop / Usjev	RPR	Species (*Pinus*) / Vrsta (*Pinus*)	RSR	Species / Vrsta	RSR
Olive / Maslina	1,540	Wheat / Pšenica	0.96	*Pinus sylvestris*	1,500	*Quercus petraea*	700
Grapewine / Vinova loza	2,620	Barley / Ječam	0.94	*Pinus halepensis*	1,400	*Quercus pyrenaica*	1,380
Peach / Breskva	2,470	Oat / Zob	0.90	*Pinus nigra*	2,100	*Quercus faginea*	1,920
Apple / Jabuka	3,770	Corn / Kukuruz	0.85	*Pinus pinaster*	760	*Quercus ilex*	2,540
Pear / Kruška	4,530	Sunflower / Suncokret	1.39			*Quercus robur*	700
Apricot / Marelica	1,890	Rice / Riža	1.07			*Populus Ssp.*	5,600
Almond / Badem	1,600					*Eucalyptus Ssp.*	3,900
Cherry / Trešnja	1,780					*Fagus sylvatica*	1,140

Table 3. Association of land use types sorted by Corine code with estimated biomass resources by sub-groups of crops or forestry species

Tablica 3. Veza između tipa zemljišta sortiranog pomoću Corine koda i procijenjenog potencijala biomase za različite tipove poljoprivrednih i šumskih ostatke

Corine / Corine		Biomass associated / Pridružena biomasa	
Code / Kod	Description / Opis	Crop / Usjev	Group / Grupa
211	Non-irrigated arable land / Obradivo zemljište koje se ne navodnjava	Winter and summer cereals / Ozime i ljetne žitarice	HARB
212	Permanently irrigated land / Zemljište koje se navodnjava		
213	Rice fields / Rižina polja	Rice / Riža	
221	Vineyards / Vinogradi	Vineyards / Vinogradi	WARB
222	Fruit trees and berry plantations / Stabla voćki i plantaže jagoda	Fruit trees / Stabla voćki	
223	Olive groves / Maslinici	Olive grooves / Maslinici	
311	Broad-leaved forest / Bjelogorične šume	Deciduous / Bjelogorica	FRB
312	Coniferous forest / Crnogorična šuma	Coniferous / Crnogorica	
313	Mixed forest / Mješana šuma	Mixed forest / Mješana šuma	

Table 4. Availability of biomass per Influence Zone (IZ) and arranged by Proximity Area (PA) from 40 to 100 km

Slika 4. Raspoloživi potencijal biomase u zonama utjecaja (IZ), sortiran po radijusu površina (PA) od 40 do 100 km

IZ	EPP (TJ_e y^{-1})	$\eta_{average}$	Available resources / Raspoloživi resursi (TJ_{th} y^{-1})				Co-firing rate / Stopa suspaljivanja (%)			
			PA40	PA60	PA80	PA100	PA40	PA60	PA80	PA100
IZ1	46176	34.6	1,598	2,612	3,313	4,393	1.2	2.0	2.5	3.3
IZ2	102978	34.1	4,673	7,277	9,928	12,071	1.5	2.4	3.3	4.0
IZ3	2865	35.3	706	1,391	2,734	4,621	8.7	17.1	33.7	56.9
IZ4	2004	34.8	1,198	2,446	4,434	6,803	20.8	42.5	77.0	118.1
IZ5	23137	33.9	1,639	3,866	7,592	12,707	2.4	5.7	11.1	18.6
IZ6	10691	32.2	1,161	1,698	1,821	1,821	3.5	5.1	5.5	5.5
IZ7	13765	37.9	3,274	6,960	13,883	23,559	9.0	19.2	38.2	64.9
IZ8	12346	37.2	449	820	1,631	3,085	1.4	2.5	4.9	9.3
IZ9	23635	37.3	310	1,324	2,279	3,459	0.5	2.1	3.6	5.5
Total	237597	-	15,008	28,393	47,616	72,519	2.2	4.2	7.1	10.9

3.4. Results of the biomass assessment

Potential biomass (HARB, WARB and FRB) has been calculated for the whole Spanish territory. A total of 12.9 Mtoe (540 PJ) potential resources could be obtained per year. Regarding the order of magnitude, those figures are similar to the figure of 10.3 Mtoe (431 PJ) per year proposed in 1999 [42] and in 2005 [43] in the Spanish Plans for the promotion of the renewable energies.

Total potential biomass resources analysed in a 100 km area around CPPs could provide 220 PJ_{th} y^{-1} of biomass capable of replacing 30 % of current coal consumption. These potential resources, however, are in some cases already in use, or may not be technically available, as the case of non exploited forest masses. Consideration of this potential involves risks on resources overestimation and on future enhanced competitiveness for resources leading to significant increments of biomass prices.

Available resources, in contrast to potential resources, only account for those biomass resources that are not being currently utilised by farmers, industry and energy sector. Available resources by IZ (summarized in Table 4) have been determined per distance (PA40 to PA100) to each IZ. By means of the IZ average electrical efficiency (calculated as average efficiency weighted by EEP) and compared to the total EEP of the IZ, the corresponding co-firing rate has been calculated.

As can be observed for the largest analysis area (100 km) significant co-firing rates are attained in IZs 3, 4, 5 and 7. Those replacement rates might entail technical difficulties, something which is discussed next.

As a preliminary result it can be observed that 10.9 % co-firing could be reached with the energy obtained yearly from available biomass resources (72.5 PJ_{th}). In case a larger area was analysed, for example 150 km radius, 122 PJ_{th} could be obtained yearly, which translates into a co-firing rate as high as 18 %. This last case has not been analysed since the available biomass of more than half of the Spanish territory is supposed to be dedicated to co-firing in CPPs.

4. Technical considerations on co-firing

Co-firing is still not applied in Spanish CPPs; none of the PF CPPs co-fires biomass in a sustained regime according to the Global Cofiring DataBase (GCDB) [44]. The only experience in a PF plant was carried out in Escucha CPP ([45-46]) and consisted of a campaign of direct co-firing tests carried out by CIRCE during 1999-2001. Co-firing was also tested in La Pereda CPP (50 MW_e CFB power plant) using biomass together with coal mine waste and coal mixtures [44], but in all cases co-firing has not been maintained. Out of the Spanish framework, the GCDB [44] reports more than 100 co-firing experiences in PF full-scale facilities in the world. Analysis of the database causes maximum reported co-firing rate in PF CPUs reaching 20 % (on an energy basis) in time limited tests. When considering only PF CPUs co-firing biomass and coal sustained in the time, it is observed that about 20 CPUs operated in 2005 with most CPUs co-firing rates under 3 % (in energy) and only few CPUs surpassing 5 %. In general, long term commercial based co-firing is currently being done at low energy rates, since then, as a matter of fact, biomass is buffered by the predominant role of coal and internal processes or equipment are not affected.

The technical attainable biomass co-firing is however larger than just 3 % substitution. Limitations depend on fuel properties (type of biomass and coal), CPP technology and systems arrangement and co-firing technology. Very different types of co-firing systems might be used for adapting biomass into coal-fired power stations as presented by acknowledged reviews of the state-of-the-art (e.g. [5, 47-49]). Direct systems are those where whole thermo-chemical processes of biomass take place together with coal into the original boiler and include systems like co-milling (raw biomass mixed with coal previous to mill), co-feeding (downstream mill mix), combined burner (adaptation of registers or ducts of original burners to biomass) and biomass burners (new additional burners or replacing coal burners). In-direct technologies, on the contrary, separate totally or partially the biomass thermal processes from coal. Technologies might separate combustion (biomass combustion gases introduced in coal boiler), may pre-treat fuel for a better adaptation by thermo-chemical processes of solid biomass (pyrolysis or upstream gasification) or of wet biomass (bio-refinery), and as well may burn biomass in a separate boiler which is coupled to the power fluid circuit of the main coal boiler.

As regard the state-of-the-art of co-firing, direct co-firing systems have been preferentially used in the power sector (only 6 experiences with indirect systems were reported in the GCDB [44]). In spite of the capacity of indirect technologies to cope with diverse technical limitations of direct co-firing, its state of development and its large cost involve important risks. Direct co-firing systems, therefore, are the systems that certainly would be installed in a first stage in Spain if co-firing finally is promoted by decision makers. Technical limitations for co-firing are a plant-specific issue where plant layout (ducts, boiler envelope and accessibility, yard), technology (burner type, size, arrangement), systems arrangement (tube banks, gas cleaning systems) or flexibility of auxiliaries (fan capacity, tempering, plant regulation) may involve important retrofitting of the plant. Those factors, considered as minor constraints, are not the cause of a hypothetical limit or ceiling for co-firing. Major constraints proposed by reference studies on co-firing state-of-the-art (as quoted above, [5, 47-48, 49] are the disimprovement of flue gas emissions, the boiler efficiency decrease, the slagging, fouling and corrosion increase, the impoverishment of fly ashes quality for recycling, the affect of to the performance of the electrostatic precipitator (ESP) and flue gas desulfuration (FGD) systems and the deactivation of the selective catalytic reduction (SCR) unit. These major constraints were proposed by diverse studies [10, 16-17, 50] as the means to determine the technical potentials of co-firing at country scale. In the present study, particularities of the fuel characteristics, the boiler and burners technology and the existence of auxiliary systems have been summarized (Table 1) in order to evaluate the capacity of CPPs to operate under co-firing operation.

4.1. Efficiency of the boiler

Efficiency loss in the boiler may reach from 0.5 to 1 percentile per 10 % coal replaced [51]. This decrease in boiler performance may be caused by both gas volume in the boiler and increase of ash deposition. Slagging and fouling are the subject of current research in co-firing. Coal combustion causes large deposition associated with mineral material and large fraction of ash in fuel. Biomass co-firing causes a lowered melting temperature of ash and larger deposition on superheaters. Experiences have shown that 10 % straw does not cause noticeable effects either on deposits or corrosion [52]. As a matter of fact, no severe corrosion is expected in PF CPUs with steam temperature under 540 ºC accordingly to [6] and

[52]. The Spanish CPPs operate with subcritical cycles whose temperature of main and re-heated steam is about 540 ºC [11].

4.2. Flue gas emissions

Dioxine emissions that could be expected as biomass incorporates chloride in the boiler, are negligible in large combustion plants [6]. SO_2 emissions are reduced by co-firing because of the lower sulphur content of primary biomass respect coal; there is furthermore an additional sulphur capture by alkaline metals contained by the inorganic volatile matter of the biomass [5-6, 16], though its role is generally secondary. NOx formation in CPPs during co-firing is influenced by the flame temperature, biomass injection, moisture, etc. Research results agree in a general reduction of NOx emissions when biomass is co-fired [5-6, 53-54]. Particulate matter emissions usually decrease by co-firing since biomass has lower ash content than coals. The aerosols, (particulate material under 10μm), however, have been acknowledged to increase by co-firing biomass with coal. This increase is however not a determinant for the feasibility of co-firing, as stated by the experimental results of the BIOMAX project [55], which also reports that stack emissions are not the main constraint for maximization of biomass co-firing.

4.3. Downstream impacts

The variation in the flue gas composition may cause either deficient operation or deterioration of equipment downstream in the boiler. SCR, ESP and FGD interact with the flue gas to reduce SO_2, NOx and particle emissions respectively. SCR systems may be deactivated by the use of biomass fuels; in Spain no single PF CPU incorporates SCR equipments and therefore it is not currently a concern, though in the medium to long term it is expected PF CPUs to upgrade their gas cleaning systems with it. Co-firing of primary biomass resources cause a reduction in the flyash quantity (biomass has lower ash content than coal) and a change in the flyash conductivity. No reduction in the ESP performance has been reported [5] and therefore ESP operation is expected to be unaffected by direct biomass co-firing at moderate rates. Chemical performance of FGD is influenced by the appearance of SO_2, HCl, alkali and heavy metals in the flue gases. Absorption of alkali will lead to larger alkaline slurry and therefore to enhancement of sulphur absorption. In contrast, the decrease of SO_2 concentration and the increase of Cl in the flue gases are negative driving forces. In general, FGD systems in CPUs have not been reported to be affected by co-firing by several reports (as in example [5-6]) and therefore neither the 13 Spanish CPUs using wet FGD nor the CPUs that might incorporate it in the future are incompatible with co-firing.

4.4. By-products recycling

The management of CPPs by-products is a concern, specially in countries where disposal in landfills is prohibited. The main by-products, gypsum from FGD, flyash from ESP and bottom ash (from discharge of boiler bottom) may be recycled in the construction and civil engineering for which they must comply with certain standards. The CPUs by-products in Spain are being partly dumped to refill part of the open mines and restore the landscape. In medium term it is probable that those practices may be re-conducted to promote recycling, and then recycling could compromise the feasibility of co-firing. Changes in by-products are expected in chemical composition and structure (affecting hydration and other properties), heavy metal content and carbon content. Gypsum may increase alkali and chloride contents when biomass is co-fired, though in general it is not a main concern. Use of flyash for concrete is limited by the EN-450-1 European Standard to flyash from CPUs with maximum 20 % (mass) co-firing and maximum participation of ash of 10 % (mass). Accounting for Spanish biomass and coal LHVs, it would lead to co-firing limits under 10 % (energy basis) in CPUs utilising either anthracite or bituminous coal [56]. The EN-450-1 European Standard restrictions on biomass mass and ash participations are currently the object of review as demanded by several power companies and concrete producers.

An alternative to the prerequisites of the EN-450-1 standard is the certification of a technical approval for flyash obtained in combustion facilities working out of the conditions marked by the standard. National approvals certifying flyash chemical properties compling with standards is a second option. As a matter of fact plants in Denmark and Netherlands co-firing biomass over 10% energy rates have not found any problems to supply their by-products to the construction and cement industry.

Bottom ash recycling is limited by the percentage of carbon in ash and by the content of harmful metals and their tendency to migrate and leach in the terrain. Since primary biomass (agricultural and forestry residues) does not incorporate these elements no problems are expected for its reuse as raw material in civil engineering.

4.5. Maximum co-firing rate

In regard to the previous statements, most relevant concerns of direct co-firing systems are the formation of deposits on superheaters accompanied by corrosion. Straw, which is considered to be one of the most troublesome fuels (as described in [5-6]) has been successfully co-fired in long term experiences. A reference in large scale co-firing of straw is the experience carried out in the Studstrup CPUs. There, 10 % straw energy caused not unnoticeable effects in the efficiency, deposit formation and boiler corrosion [52]. An energy replacement of 20 %, however, multiplied the corrosion tendency threefold.

The biomass resources accounted for the present study are either woody residues (WARB and FRB) or herbaceous residues (HARB). Woody residues are not as troublesome as the straw in terms of ash content and potential effects in superheaters slagging, fouling and corrosion, when co-fired in PF CPPs. Under this scope, and given straw is as troublesome as the rest of the herbaceous residues, a priori biomass could be co-fired in a 10 % energy share in any of the Spanish CPPs.

As a matter of fact, when reviewing the cutting-edge full scale direct co-firing PF CPUs it is observed that energy substitutions above 10 % have been attained and maintained in Denmark (Studstrup, 10 % straw), in Netherlands (Borselee 10 % wood pellets and olive pulp mainly; Amer 9, wood pellets and olive pulp up to 10 %), Belgium (Rodenhuize 4, up to 12 % of wood pellets and olive pulp) and United Kingdom (Didcot Oxfordshire, 10 % of multiple biomass types; Ferrybridge, 12 % wood and olive residues mainly) [44]. Coal and biomass could therefore be co-fired in Spain in a sustained way with the current co-firing technologies achieving coal substitution rates of up to 10 %. Beyond this limit co-firing is possible, feasible or even could be profitable, though special attention must be placed in the type of coal and biomass used, and to the specific configuration of the internal heat exchangers.

5. Implementation of co-firing potentials at country level: Spain and Croatia

5.1. Technical co-firing potential in Spain

Co-firing potential in Spain is the result of a compromise among resources availability and co-firing technical limitations. In consumption centres where available biomass surpasses the technical ceiling, 10% is considered the co-firing potential. This technical limitation is surpassed in IZs 3, 4, 5 and 7. Particularly IZ4 provides enough available biomass in PA40 to replace 10% of coal energy. IZ 3, 5 and 7 could cover a hypothetical demand for 10 % energy co-firing with the resources inside PA60. This reveals that biomass could be obtained more easily from local resources, and therefore transport costs may imply a lower biomass cost with respect to IZs that consume whole available resources in PA100. IZ8 achieves almost a 10% co-firing energy rate in PA100.

The contribution of all consumption centres (by IZs), once the biomass resources have been moderated to provide not more than 10 % of the energy by IZ, amouth to 36.5 PJ_{th} equivalent. These biomass resources could contribute yearly to the production of 13 PJ_e, which represent a co-firing rate of 5.4 %. This is the current attainable co-firing in Spain, and it relies on three main hypothesis: a sustained coal energy production of the CPPs by 2015, the use of only non used (available) biomass resources and the constraint of a maximum co-firing energy rate of 10 %.

This technical feasible 5.4 % co-firing potential is equivalent to 652 MW_e of installed power, which would by far duplicate the current power production with biomass in Spain (8.6 PJ in 2007 [57]). Renewable energy plans established the political goal of 1,567 MW_e installed power by 2010. Co-firing could contribute with 652 MW_e which represents 41 % of the final objective and 67 % of the current gap, without needs of biomass imports, energy crop expansion and without interfering with the current biomass markets.

5.2. Economical feasibility of co-firing in Spain

Achievement in the short term of a relevant role of co-firing in Spain similar to the figures obtained above for the Spanish CPPs is not a question of technology capacity, but of economics and decision making.

For a favourable framework, active economic and policy actions must accompany the process regarding co-firing dissemination. In terms of economics, the price of biomass (per thermal unit) is more expensive than the coal price. Additionally reforms for adapting CPPs to direct co-firing systems involve certain investment costs. The slight decrease in the boiler efficiency that biomass may cause when co-fired (as has been discussed in the corresponding section) would furthermore lead to a lower energy production per fuel. On the positive side, co-firing reduces CO_2 emissions and generates savings for companies on CO_2 credits. In certain countries subsidies for retrofitting are available, though it is not the case in Spain at the very moment.

In Spain the 54/1997 Electricity Law contemplated the production with renewable energy sources under a special regime where electricity sales would be compensated with an extra bonus. Royal Decrees have set and updated the bonus to power production from 1998, which, in the case of biomass, has not lead to a significant evolution, partly as result of no discrimination of bonus quantity sorted by biomass resource type [58]. In the case of co-firing, incentives were allowed only from 2007 (Royal Decree RD661/2007), and, differently to biomass power plants, bonus was not specified in the decree. In order to obtain a bonus for a co-firing plant, the decree laid down that companies must pass an administrative process in order to carry out evaluation of each single initiative by providing the engineering project, by defining biomass resources to be used and by describing involved costs for both biomass procurement and plant retrofitting.

At present, no single bonus has been assigned to any CPP in Spain. In order to evaluate the feasibility and profitability of co-firing under the present framework, an assessment of co-firing profitability has been carried out. Coal prices of 0.9 €cent per kWh (equivalent to 0.25 €cent per MJ_{th}) obtained from international markets has been used; prices per kWh of biomass energy surveyed by CIRCE ranged 1.4 to 2.0 €cent (equivalent to 0.39 to 0.55 €cent per MJ_{th}) for clean pollutant free biomass resources. The price of energy sales has been obtained from 2007 report of power network operators, in average 5.5 €cent per kWh (1.5 €cent per MJ_e). CO_2 credits price of 20 € t_{CO2}^{-1} has been used. CPPs considered will operate until 2015 and have on average an efficiency of 36.5 % (from data on fuel consumption and power production [59]) with 6,750 annual equivalent working hours [13]. A co-firing rate has been considered to be 10 % (energy), causing a decrease in boiler efficiency of 1 percentile [51] and an increase of power consumption in auxiliaries (biomass pre-treatment) of 610 MJ t_{bio}^{-1} [60] (assuming a biomass size reduction to an average particle size of 3 mm). Co-firing retrofitting costs are significantly variable depending on CPP technology and type of co-firing system. Literature provide values up to 1000 \$ kW_e^{-1} [61], though in general for direct co-fring systems investment costs are in a lower range: between 50 and 300 \$ kW_e^{-1} [5], between 230 and 600 € kW_e^{-1} [60] or around 370 € kW_e^{-1} [62]. Achieving 10 % of co-firing (energy basis), as has been assumed in the present work, relies on the use of direct co-firing technologies like mixed burners or new biomass burners that involve relevant costs. For this case, an investment cost of 370 € kW_e^{-1} obtained from full-scale experience in a PF CPU has been selected as retrofitting cost. Operation and maintenance (O&M) costs used are based in reported experience for a PF CPU [62] with a cost of 0.17 €cent kWh^{-1}. Investment and O&M costs are in the range of values obtained in the only real experience on co-firing in a PF CPU in Spain (Escucha CPP) [45].

Economic analysis reveals that with the previous parameters profitability of co-firing need a bonus for the energy production of 0.7 to 2.6 €cent per kWh of electricity produced (equivalent to a range from 0.19 to 0.72 €cent MJ_e^{-1}) depending on fuel price (either 1.4 or 2.0 €cent kWh^{-1} respectively). These figures have been calculated on the basis of quite variable parameters, and therefore a proposed bonus range for co-firing must be regarded as representative for a general country approach, but not as the reality for each specific CPU.

5.3. An appraisal on the Croatian case

The potential of co-firing at a country level as presented in this paper, depends on the CPPs installed power, on resources availability and on technical capacity to adapt biomass in CPPs. The Croatian case is to a certain extent an opposite case of the Spanish case. Croatia has only a coal power plant (Plomin, 125 MW_e) though further expansion of coal utilization is expected in future scenarios [63]. Since the technical potential is limited to 10 % of coal power production, at first sight co-firing could contribute with 12.5 MW_e of renewable energy. In 2007 Croatia accounted for only 2 MW_e producing barely 7 GWh of electricity [63]. Even though biomass plants are planned, co-firing could give an important boost towards the targets by 2020 (140 MW_e of installed power [64]) 10 % co-firing would require approximately 0,9 PJ of biomass energy resources, which represents only 1 % of the Croatian biomass potentials (up to 90 PJ) [65].

With respect to the legal framework, the Energy Act came into force in 2007 in Croatia [63]. Under this framework biomass power production is supported with a tariff of 15 €cent kWh^{-1} [63], though co-firing technologies are not included as candidates.

As summary, Croatia has sufficient biomass resources to fully accomplish future needs for power production, including utilization of important co-firing rates. However, as in the Spanish case, the lack of specific incentives for co-firing, may keep this type of low cost energy option undeveloped.

6. Conclusions

The country analysis of Spain has served to present a methodology to carry out studies for co-firing capacity and feasibility at country level. Sufficient results have been obtained to provide figures on the attainable potentials. The existence of political incentives and the price of the resources has shown to be more relevant for the widespread use of co-firing, than the current technological limits for the case study.

Recent Spanish national regulations have included biomass co-firing into the renewable energies candidate for obtaining an extra bonus (Royal Decree 661/2007) for the production of electricity. From this scope the framework for co-firing in Spain is a priori favourable for development of co-firing systems in coal power plants (CPP) in the medium term. From the 20 Spanish CPPs with a total of 39 coal power units (CPUs) 38 of them use pulverized fuel (PF) technologies. Most of the units will continue in operation with a slight constant decay until 2015, when some units may shut down and important retrofitting is expected in the remaining units. Therefore co-firing in the short and medium term has a large potential to contribute to the biomass power production in Spain.

The total potential resources sum 220 PJ_{th} y^{-1}. From those resources, a part is already being used for energy or other uses. When accounting for only the currently non utilised agricultural biomass resources and forestry technically available resources (accessible and of simple mechanization) total resources decrease from 220 to 72.5 PJ_{th} y^{-1}. Among the different consumption zones (IZs) in Spain available biomass could replace from 3 to 100 % of the coal consumed in CPPs.

Nevertheless adaptation of large biomass rates replacing coal in PF CPPs involves certain difficulties and risks for the operation of the CPPs. According to the very state-of-the-art of direct co-firing technologies, it has been stated that fouling, slagging and corrosion are the major constraints for the use of biomass in CPPs. It has been stated that in the medium term 10% co-firing is attainable with already available and probed technologies. When co-firing replacement percentages by CPP are constrained to a maximum of 10%, the sum of total biomass available for co-firing in Spain achieves 36.5 PJ_{th} y^{-1}.

This technical feasible co-firing potential could be used to produce up to 13 PJ_e (equivalent to 652 MW_e of installed power) capable of substituting 5.4 % of the coal energy used by CPPs in Spain. The implementation of co-firing could almost duplicate the current power production with biomass in Spain and contribute with a share of 41 % to the goals of the energy plants on biomass power production, covering up to 67 % of the current gap. This co-firing capacity is based on national resource consumption without interfering with the current biomass markets. That is, no rises of the biomass prices could be expected by achieving 5.4 % co-firing. This rate could be increased by means of biomass imports and energy crops expansion.

These co-firing potentials and the contribution to the Spanish goals on biomass power generation could be achieved with an economical support of 0.7 to 2.6 €cent per kWh of electricity produced by co-firing biomass (an equivalent range from 0.19 to 0.72 €cent MJ_e^{-1}). Co-firing, from a pure economical analysis, as many other renewable energy resources, will require a bonus additive to the sales of electricity, but on the hypotheses finally assumed, three to six times cheaper than other bonus for biomass energy production in dedicated power plants. As well co-firing savings on GHG emissions may be a carrot for company strategies and decision takers, since it can reduce the current deficit in the coverage of emissions assigned to the sector. In conclusion co-firing is at present a cost efficient solution, capable of contributing significantly to the Spanish objectives on biomass electricity production and on GHG emissions reduction.

Acknowledgements

To the Spanish Education and Science Ministry for the financing of the project ENE2005-00304/ALT with title "Greenhouse gas emission real potential reduction determination with co-firing in Spain".

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