Fuel Processing Technology 142 (2016) 296–304

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Techno-economic analysis of a 15 MW corn-rape oxy-combustion power plant

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ARTICLE INFO

Article history:
Received 14 July 2015
Received in revised form 8 October 2015
Accepted 13 October 2015
Available online 2 November 2015

Keywords:
Oxy-combustion
Biomass
Energy analysis
Economic analysis
CO_2 capture

ABSTRACT

Oxy-combustion is a promising technology to enable the capture of CO_2 from power plants based on diverse raw material. This paper describes and compares the results of technical and economic viability studies of a 15 MW power plant based on a corn-rape blend oxy-combustion, a bituminous coal-combustion and a bituminous coal oxy-combustion located in the north of Spain. Technical simulations were implemented in Aspen Plus© software. The economic viability studies were based on the typical economic indicators such as net present value, rate of return, specific total plant investment, cost of electricity, cost of CO_2 avoided and energy consumption for CO_2 avoided. A sensitivity analysis was carried out in order to identify the most important factors affecting the investment risks. The use of a cryogenic air separation unit was associated with a reduction in oxy-combustion plant viability. While coal-combustion process reported an enough profitability, a supplementary public grant of 63 €/MWh and 57 €/MWh were required in coal oxy-combustion process and biomass oxy-combustion process respectively to obtain a positive profitability. A stability of raw material and electricity markets was found to be necessary to improve a risk reduction for the potential investment.

1. Introduction

One of the most significant current discussions in environmental sciences is the increasing of the energy demand all over the world due to the population growth and the technological and economic development. Organization for Economic Co-operation and Development (OECD) countries have increased their energy demand from 4500 Mtoe in 1990 to 5500 Mtoe in the last 2014. A maintenance of this energy demand is expected for the next 25 years [1]. On the other hand, China energy demand has increased from 1000 Mtoe to 3500 Mtoe in the same period of time, but there is an expected stability around 4000 Mtoe at 2040. As China slows, then India, Southeast Asia, the Middle East and parts of Africa and Latin America take over as the engines of global energy demand growth for the next 25 years [1]. The increasing of demand of these countries is expected to be more than 8500 Mtoe in 2040. This situation is being aggravated by the raising turmoil in the Middle East countries, which establish doubts over the future oil balance and supply [1]. In addition, geopolitical and market uncertainties are set to propel energy security high up the global energy agenda and have resurged the debate over the security of gas supply to Europe. It is becoming increasingly difficult to ignore this situation.

Energy production from fossil-fuel combustion, including coal, oil, oil shale, natural gas and gas shale, results in the emission of greenhouse gases, being CO_2 the dominant contributor [2]. The growing problem dealing with the increase of greenhouse gas emissions and their potential impact on climate change requires further investigations of alternative technologies to reduce CO_2 emissions.

According to this problem, the European authorities [3] established the Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC [4]. At the same time, the Decision No. 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the community's greenhouse gas emission reduction commitments up to 2020 was published. Both rules were the legal basis of the European Union battle against climate change. As a consequence, the Spanish Government established a Renewable Energies Project for the period 2011–2020 [5,6] to reach a minimum of 20% of the total energy production pool by renewable energies in 2020 (also called strategy 20-20-20).

There is a wide range of ways of carbon-free or reduced-carbon sources of energy and combustion with CO_2 capture [7,8]. It is generally accepted that a drastic reduction in CO_2 emissions is necessary in a short

Abbreviations: OECD, Organization for economic co-operation and development; CCS, carbon capture and storage; RYIELD, aspen block for simulating solid reactions with yield specifications; RGIBBS, aspen block for simulating solid reactions by minimizing the free Gibbs energy; ASU, air separation unit; TEC, total equipment costs; CEPCI, chemical engineering plant cost index; FCI, fixed capital investment; TCI, total capital investment; CCA, cost of CO_2 avoided; SPECCA, specific primary energy consumption for co_2 avoided; EBTF, European benchmarking task force; COE, Cost Of electricity; NPV, Net present value; IRR, Internal rate of return.

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http://dx.doi.org/10.1016/j.fuproc.2015.10.020
0378-3820/

period of time and among the various strategies proposed, Carbon Capture and Storage (CCS) is considered as a valid solution for the next 50 years [9]. Between the different CCS technologies, oxy-combustion with CCS is a promising technique because it can be used as a CO_2 sink, contributing to reduce the greenhouse effect. In an oxy-combustion process the fuel is usually burned in a mixture of oxygen and a CO_2 flue gas instead of air. Although it is theoretically possible to burn fuel in pure oxygen, the recycled flue gas is generally used to control flame temperature and make up the volume of N_2 to ensure enough gas to carry the heat through the boiler [7]. N_2 is separated from O_2 in order to avoid NO_x formation and to produce a rich CO_2 concentration stream at the final of the process. This stream can be used to CO_2 capture and storage.

Between possible oxy-combustion raw materials, biomass is the term used for all organic material such as stems from plants, trees and crops that are susceptible to be converted into energy [10,11]. Biomass can be burned directly in waste-to-energy plants to produce steam and generate electricity [12].

The electricity generation by energetic crops processing in plants between 10 and 15 MW was included in the Renewable Energies Project by the Spanish Government.

So far, however, there has been little discussion about using biomass blends as the only raw material in oxy-combustion processes for electricity producing.

In previous works, the oxy-combustion of several biomasses was studied and the biomasses were compared in terms of best oxy-combusting characteristics [13]. Afterwards, the oxy-combustion conditions of the selected biomasses were optimized using the surface response methodology (results pending publication) and a mathematical model of the transport phenomena occurring in the oxy-combusting particles was applied [14].

The aim of this work was to study the technical and economic viability conditions of a 15 MW corn-rape oxy-combustion power plant for a region in the north of Spain. This study was completed by analysing the same process properties of a combustion and oxy-combustion using a bituminous coal as raw material. This coal was obtained from a coal mine located on the north of Spain. The comparison of the three plants proposed was successful to obtain important conclusions of the application of thermal biomass processes as an alternative to traditional coal combustion processes.

2. Materials and methods

2.1. Materials

The corn and rape biomasses and the coal used in this study were taken from the region of Leon, Spain. The bioresidues were characterized to determine their proximate and ultimate analyses and corresponding heating values, which were necessary to run the simulations of this study. The moisture content was determined gravimetrically using the oven drying method (D 4442). The higher heating value (*HHV*) at a constant volume was measured by an adiabatic oxygen bomb calorimeter (D 240). Proximate determinations were made in accordance with modified procedures from E 870 (Standard Methods for Analysis of Wood Bioresidues), D 1102 (ash in wood) and E 872 (volatile matter). For the ultimate analysis, a LECO model CHN-600 instrument was used to determine the carbon, hydrogen and nitrogen content (D 5373). Sulphur was analysed using a LECO model SC-132 instrument (D 4239). As corn and rape are lignocellulosic bioresidues, the cellulose, hemicellulose and lignin compositions of the bioresidues were determined by duplicate analyses of neutral detergent fibre (NDF), acid detergent fibre (ADF) and crude fibre [7] in ground samples using an Ankom 200 fibre analyser.

In coal case, the proximate and ultimate characteristics and corresponding heating values, which were necessary to run this study simulations, were obtained from the technical paper of the region power plant [15].

Table 1
Proximate analysis, ultimate analysis, calorific values, composition and properties corresponding to the coal, corn and rape used in this study.

Material	Coal	Corn	Rape
Proximate analysis			
Moisture (%)	12.0	8.0	9.2
Volatile matter[a] (%)	32.0	76.8	80.4
Ash[a] (%)	25.5	5.7	2.6
Fixed carbon[a,c] (%)	30.5	17.5	17.0
Ultimate analysis			
C[b] (%)	65.1	48.8	49.7
H[b] (%)	2.9	6.2	6.3
N[b] (%)	1.4	0.5	0.2
S[b] (%)	1.9	0.1	0.2
O[b,c] (%)	28.7	44.4	43.6
Calorific value			
HHV (MJ/kg)	25.08	18.45	19.49
Composition			
Cellulose (%)	–	18.6	25.7
Hemicellulose (%)	–	29.7	21.6
Lignin (%)	–	12.0	7.4
Properties			
Grindability index	50	27	
Dielectric constant	5.0	2.5	

HHV = high heating value.
[a] As received.
[b] Dry ash free basis.
[c] Calculated by difference.

Table 1 Summarizes the proximate analysis, ultimate analysis and the heating values obtained for both corn and rape bioresidues and for bituminous coal.

2.2. Methodology

This study was divided into three parts, as it is shown in Fig. 1. First of all, a technical simulation was performed based on two raw materials: a corn-rape blend and a bituminous coal as it was previously explained. The reference process was a 15 MW

biomass oxy-combustion power plant. However, very little information was found in the literature on the question of industrial size power plants based on biomass. Otherwise, actual investigations are mainly focused on power plants based on coal or a mixture of coal-biomass as material raw. This was the principal reason why it was decided that the best method to adopt for this investigation was to compare the biomass process based on biomass oxy-combustion (innovative method) with two other processes: an equivalent 15 MW power plant based on coal oxy-combustion (intermediate method) and, finally, the equivalent 15 MW power plant based on coal combustion (traditional method).

Once the three power plants were simulated and the main thermal and power variable values were obtained, an economic viability study was developed for each power plant. The aim of this second part of the paper was to compare the economy of the different processes by the different raw material points of view. Many different methods were found in literature about this study proceeding but a semi-rigorous method was finally chosen to obtain the main viability parameters, such as the net present value and the rate of return.

As the last part of this paper and after the previous comparison, a sensitivity analysis of the biomass power plant was performed.

2.2.1. On the technical simulations

All technical simulations were implemented in ASPEN PLUS© v.11.1 [16] industrial software using its improved solid modelling capabilities. The technical simulation descriptions were divided into the two different process simulations taken into account: combustion and oxy-combustion. In the first case, only coal was used as raw material. In the second, coal and biomass were used as possible feed materials.