ECONOMIC CONSIDERATION OF PRODUCING FERTILIZER FROM COAL-FIRED FLUE GAS: APPLICATION OF BULGARIAN EXPERIENCE TO CASE STUDY OF PORTUGAL

Ryunosuke KIKUCHI¹, Yontcho G. PELOVSKI², Sandra M. SANTOS¹

¹ESAC – Polytechnic Institute of Coimbra, Bencanta, 3040 Coimbra, Portugal.
Tel: +351 (239) 802287; fax: +351 (239) 8022979; e-mail: kikuchi@mail.esac.pt
²University of Chemical Technology & Metallurgy, 8, Kl. Ohridski blvd, 1756 Sofia, Bulgaria

ABSTRACT

A Bulgarian project at Maritsa East power station demonstrated the proper transformation of air pollutants (SO₂ and NOₓ) into nitrogen fertilizer. Although this technology has not been put into practice in Bulgaria, it seems feasible on an industrial scale and so it may help to ease Portugal’s reliance on imports of nitrogen fertilizer and thereby contain the outflow of Portuguese funds. The data collected from the Maritsa East project are therefore applied to discuss a case study of Amarante thermal power station in Portugal, which annually imports 27 million Euro of nitrogen fertilizer. The agricultural sector indicates it is willing to support 20% of the plant installation cost and 100% of the operating cost at a thermal power station. Thus, a Portuguese farmer can obtain by-product fertilizer that is cheaper than commercial fertilizer at current prices as compensation for financial support of fertilizer production at a thermal power station.

KEYWORDS: desulfurization, fertilizer, flue gas, sulfur dioxide, willingness to pay
INTRODUCTION

A polluter may want to introduce an antipollution process, and needs initial capital and the operating cost for the process; on the other hand, the by-product generated by the antipollution process can be used by a third party (i.e. a by-product user).

Air pollution can affect the environment both directly and indirectly [1]. When sulfur oxides (SO\textsubscript{2}) gas is present in high concentrations, it can cause damage to the natural environment (e.g. acid rain) and affect human health (e.g. asthma) [1]. SO\textsubscript{2} is mainly emitted from thermal power plants and industrial plants that burn fossil fuels such as coal [2, 3]. Flue gas desulfurization (FGD) has been applied in many parts of the world to remove SO\textsubscript{2} from flue gas generated by burning fossil fuel, and the wet limestone process is now one of the leading methods of FGD. In the journal of the Southern Agricultural Economic Association (Minnesota, USA), it was pointed out that application of FGD by-products would be beneficial according to a study based on a linear optimization model [4]. However, their application is not related to agriculture but mainly to civil construction (e.g. highway repairs).

FGD by-product options were assessed by the expert commission of the European Bank for Reconstruction and Development (EBRD) at Maritsa East lignite-fired power station in Bulgaria, and some options are reported [5]: gypsum, elemental sulfur, concentrated SO\textsubscript{3}, sulfuric acid and ammonium sulfate (nitrogen fertilizer, abbreviated as N-fertilizer). Considering the commercial value of fertilizer in domestic and international markets, the EBRD report concludes that it is advantageous to link FGD projects with by-product fertilizer. A number of methods for transforming SO\textsubscript{2} into N-fertilizer have been commercialized: GESSI wet process, Krup-Walther wet process, regenerable sodium process, and so on [5, 6]. However, these processes discharge wastewater, so it is necessary to install a wastewater treatment unit. Moreover, these processes are not expected to properly treat flue gas having a high concentration of SO\textsubscript{2} (SO\textsubscript{2} in particular) generated by burning local lignite. A semi-demonstration test using the electron beam dry process (abbreviated as the EB process) was therefore conducted at Maritsa East power station in Bulgaria. In this process, free radicals (OH, O and HO\textsubscript{2}) originating from electron beam irradiation oxidize SO\textsubscript{2} and SO\textsubscript{3} (and/or NO\textsubscript{x}) to form reactive intermediates, which then react with ammonia to form ammonium sulfate fertilizer (and/or ammonium nitrate fertilizer) [7]. The by-product fertilizer may contain a considerable amount of ammonium nitrate if the flue gas is rich in NO\textsubscript{x}. The treated flue gas and the fertilizer particulates can easily be separated in an electric precipitator. This system is not a wet-type (scrubbing type) process but a dry-type process which does not discharge wastewater [7]. Industrial application of this technology has not yet been carried out in Bulgaria or elsewhere. However, since the technology is promising in terms of transforming pollutants into a useful product, it would be a lost opportunity for European agriculture and the environment if the Bulgarian experience were to be ignored.

This paper discusses the economic aspects of applying the above-mentioned experience to a Portuguese project (introducing FGD to Portugal) and presents the data as a case study of an industrial project of mutual support between the agricultural sector and the energy sector. It also evaluates the economic eagerness of by-product users (i.e. the agricultural sector) according to the willingness-to-pay (WTP) approach.

MARITSA EAST PROJECT AND AMARANTE PROJECT

The main purpose of this paper is to present an economic assessment of producing N-fertilizer from coal-fired flue gas, so the technical background of this process is summarized as much as possible. The Maritsa East project in Bulgaria and the Amarante project in Portugal are presented briefly as follows.

Maritsa East project

Bulgaria has confronted some major issues since economic transition began in 1991: accession to the European Union (EU), economic confusion, security of its energy supply, privatization, competitiveness of national industries, etc. To be accepted into the EU, it is particularly important for Bulgaria to reduce air pollutants (e.g. SO\textsubscript{2} and NO\textsubscript{x}) emitted from thermal power stations. Furthermore, the agricultural sector accounts for 50% of gross domestic product [8], so it is also important to improve this sector. The Ministry of Environment and Nationalna Electricheska Kompana (NEK) intended to demonstrate the economic and technical performance of the EB process on a semi-demonstration scale by transforming 15,000 m\textsuperscript{3}/N/h coal-fired flue gas (5,500 ppm SO\textsubscript{2}, 140 ppm SO\textsubscript{3}, 390ppm NO\textsubscript{x} and 200 mg/m\textsuperscript{3} fly ash) into N-fertilizer (mainly ammonium sulfate) at Maritsa East power station.

The locational relation between the power station and the fertilizer company was attractive for this project. The fertilizer company Agrobiochim (Stara Zagora) is located about 50 km north of Maritsa East power station, and it annually produces 125,000 tons of ammonium sulfate which is mainly exported. Another company, Neochim in Dimitrovgrad, is also near Maritsa East. This
company can supply about 150,000 tons/year ammonia to the project and produces 750,000 tons/year ammonium nitrate. Although the project sometimes encountered economic and technical obstacles, it managed to overcome them thanks to financial aid and technical support from the International Atomic Energy Agency (IAEA). Construction of the test plant itself (see figure 1) was achieved through great effort on the Bulgarian side with support from the IAEA (No.BUL/8/013). The final evaluation was reported in Sofia on 7 September 2004, and the results proved that (i) the quality of the by-product fertilizer is comparable to that of commercial N-fertilizers, (ii) 99% SO$_2$ and 87% NO$_x$ can be removed from the flue gas, and (iii) energy consumption is unexpectedly low.

**Amarante project**

Air polluters may be unaware of the demand for fertilizer in Portugal. Potash fertilizer and phosphate fertilizer are not completely absorbed into plants in one cropping, and their fertilizing effects are expected to last through the next cropping too. That is, they have residual fertilization effects [9]. However, nitrogen fertilizer should be applied each year [9]. Figure 2 shows the recent trend in import of N-fertilizer to Portugal [10]. It follows from figure 2 that the import value of N-fertilizer has been dramatically increasing: the import value (27 million Euro) in 2003 was about three times higher than that in 1999. In other words, paying more to import N-fertilizer accelerates the outflow of Portuguese money. This is not favorable to the international balance of trade in Portugal. Making N-fertilizer from SO$_2$ flue gas may help to contain the outflow of Portuguese money.

SO$_2$ emissions have fluctuated and have not shown a downward trend in Portugal. According to national statistical data [11], about 400,000 tons of SO$_2$ is annually discharged to the atmosphere in Portugal, and the energy sector accounts for 60% of this amount. Although FGD has not yet been introduced in Portugal, at present two FGD projects are planned or under consideration at Sines power plant (1,200 MW) and Amarante power plant (600 MW). The introduction of FGD may give rise to the problem of how the Portuguese energy sector is going to manage the construction cost at the first stage and the operating cost over the long term. It is not advisable to increase the price of electricity to cover such costs because Portugal is already one of the most expensive countries in the European Union for supply of electricity [12]. It would merely create ill feeling among the general public and industries to impose a higher price.

As to social and economic aspects in Portugal [13], the employee share in primary industry is high (e.g. 32% in the central zone) and the wage rate in primary industry is comparatively low. It seems worthwhile from the social, political and economic viewpoints to contemplate linking FGD projects (SO$_2$ reduction) in the energy sector with utilization of the resulting by-product in the agricultural sector.

The data collected from the Maritsa East project are applied to discuss the synthetic introduction to Amarante thermal power station of the EB process for converting SO$_2$ into fertilizer.

**BY-PRODUCT USER AND BY-PRODUCT TYPE**

If a by-product user feels that it is advantageous to obtain the by-product, it can be expected that the user will provide economic support to the environmental project. The initial capital and the operating cost of the project may be partially or totally covered by this financial support. Thus, this method contributes both to reducing the economic burden on the polluter and to making the by-product user's productivity more competitive.

The wet scrubber FGD process (also known as the wet limestone process) generally uses limestone slurry as an absorbent [14, 15]. SO$_2$ is transformed into calcium sulfate (CaSO$_4$, equivalent to natural gypsum). Limestone is abundant all over the world, easily handleable and cheap [15], and utilization of limestone has popularized the process (see figure 3 redrawn from [16]). Though the FGD by-product gypsum is utilized in various sectors (e.g. wallboard, road base, cement, etc.), the quantity of FGD gypsum used is very small and its utilization rate (= utilization/production) is low, about 3% on average [17]. The FGD by-product gypsum has shown limited market potential and is usually disposed of [18]. Common to all residues from the various wet FGD systems applied in Europe is the fact that they are highly contaminated and in most cases classified as hazardous [19].

The Maritsa East project intended to transform SO$_2$ and NO$_x$ into by-product fertilizer (mainly ammonium sulfate) comparable to commercial N-fertilizers. The following advantages for using ammonium sulfate are reported [20]: (i) ammonium sulfate containing two primary nutrients - 21% N and 24% S - is a cost effective fertilizer; (ii) ammonium sulfate can be applied directly as a fertilizer or used as an ingredient in a compound fertilizer; and (iii) positively charged ammonium ions attach to soil particles, remaining in the root zone until needed by the plant, not leaching into the groundwater.

**VALUATION APPROACH FOR WILLINGNESS-TO-PAY (WTP)**
The agricultural sector's willingness-to-pay (WTP) toward an environmental project (i.e., FGD installation) in the energy sector can be evaluated using a mathematical approach. Only essential parts are briefly described below to help the interpretation of the derived formula.

The individual can be assumed to maximize the utility function \( u(x) \) under \( p \cdot x = Y \), where \( x \) is the demand vector, \( p \) is the price vector and \( Y \) is income [21], and solving this maximization problem would give the demand function \( x(p, Y) \). Applying the Lagrange multiplier \( \lambda(p, Y) \) results in an indirect utility function:

\[
V(p, Y) = u(x(p, Y)) (1)
\]

Letting the above-mentioned function be the differential equation of the second order:

\[
\frac{\partial V}{\partial p_i} = -\lambda \frac{\partial x_i}{\partial p_i} - \frac{\partial Y}{\partial p_i} = \lambda. (2)
\]

Substituting formulas (2) and (3) in formula (4):

\[
\Delta V = \sum_i \left[ \left( \frac{\partial V}{\partial p_i} \right)_{\partial p_i} + \frac{\partial V}{\partial Y} \right] dY (4)
\]

Combining formulas (7), (8) and (9), where \( \gamma = \gamma(Y) \) (7), where 

\[
\gamma(Y) = \frac{a}{Y} (7)
\]

Substituting formula (6) in (5), where 

\[
\Delta V = \frac{\gamma}{\lambda} \sum_i \left[ \frac{\partial V}{\partial p_i} \right]_{\partial p_i} + \frac{\partial V}{\partial Y} \right] dY (5)
\]

\[
\Delta V = \frac{\gamma}{\lambda} \sum_i \left[ \frac{\partial V}{\partial p_i} \right]_{\partial p_i} + \frac{\partial V}{\partial Y} \right] dY (6)
\]

Substituting formula (6) in (5), where 

\[
\gamma = \gamma(Y) \frac{a}{Y} (8)
\]

Combining formulas (7), (8) and (9), where 

\[
\gamma = \gamma(Y) \frac{a}{Y} (9)
\]

Combining formulas (7), (8) and (9), where 

\[
\gamma = \gamma(Y) \frac{a}{Y} (10)
\]

When formula (11) is applied to evaluate the WTP for an FGD project with production of by-product fertilizer, the legends in the formula have the following meanings: the fertilizer cost is reduced from \( P_0 \) (present fertilizer) to \( P_1 \) (FGD by-product fertilizer), which is the economic merit; to obtain the by-product fertilizer, a farmer must invest an amount of \( Y^0 \cdot Y^1 \) in the FGD project which removes \( SO_2 \) in the energy sector and makes the by-product fertilizer, so the farmer's income will be reduced from \( Y^0 \) (present income) to \( Y^1 \) (remaining income after deduction of investment); \( \alpha_i \) represents the ratio of the present fertilizer cost to present income; and the maximum of the farmer's WTP for the FGD project can be calculated from setting \( \Delta V = 0 \).

**CASE STUDY DATA**

In terms of applying the WTP method to this evaluation, it is necessary to substitute each value in formula (11): (i) based on the Bulgarian project, utility data for the EB process are recalculated to conform to the case study, (ii) the construction cost for the case study is deduced from published information [24, 25, 26, 27], and (iii) local costs are based on national statistical data [28, 29, 30, 31].

Economic data for FGD units (EB process)

The economic performance of the EB process for removing \( SO_2 \) and producing N-fertilizer is calculated on the basis of 1,800,000 Nm³/h coal-fired flue gas generated from a 600 MW power station. Main components of the obtained fertilizer are 92% ammonium sulfate, 1% ammonium nitrate and 7% others such as silicon oxides (a chief component of the earth's crust). In this case, nitrogen (N) content is 19.3% in the by-product fertilizer. These data are summarized in table 1.

It follows from table 1 that 98,400 tons/year of by-product fertilizer is produced by purifying 1,800,000 Nm³/h SO₂ flue gas at an annual operating cost of 7,499,100 Euro (excluding annual depreciation). Dividing this cost by 98,400 tons gives a unit cost of the by-product fertilizer of 76 Euro (with 19.3% N) corresponding to 394 Euro/ton-N. This means that the energy sector's sale (i.e., agricultural sector's purchase) of the fertilizer priced at 76 Euro would cover the operating cost for \( SO_2 \) control at a thermal power station.

**Economic data for Portuguese agriculture**

To apply formula (11), it is necessary to introduce income, fertilizer consumption, and fertilizer cost. The N-fertilizer price (as N) generally depends upon the type and the chemical form. However, national statistical data do not contain detailed information about fertilizer consumption by type. The fertilizer price per N and other statistical data are summarized in table 2.

As seen in table 2, a farmer spends 257 Euro/year on N-fertilizer and uses 0.38 tons/year (as N). Converting these values, the unit price of N-fertilizer is 676 Euro/ton-N. A farmer will use 0.38 tons/year of N contained in the by-product fertilizer to achieve the same productivity assuming that the farmer does not have to meet any special requirements. Dividing 257 Euro by 11,952 Euro of income gives a ratio \((\alpha_i)\) of N-fertilizer/income of 0.022.
RESULTS

The case study presented in table 1 produces 98,400 tons/year of by-product fertilizer with 19.3% N, and it is analogized that a farmer consumes 1.97 tons/year of by-product N-fertilizer with 19.3% N. Dividing 98,400 tons/year by 1.97 tons/year/capita, 49,942 farmers (11.2% of all farmers) can enjoy the benefit of by-product fertilizer from an SO\textsubscript{2} removal unit at a thermal power station. The obtained results indicate that the agricultural sector is willing to support 20% of the initial cost (construction) of 35,000,000 Euro for an SO\textsubscript{2} reduction project at a thermal power station and that 100% of the operating cost including annual depreciation can be covered by the agricultural sector's purchase of by-product fertilizer at 62.7 Euro/100kg-N in Portugal.

DISCUSSION

As has been discussed above, it is apparent that it would be advantageous for SO\textsubscript{2} abatement if there were cooperation between the energy sector and the agricultural sector in Portugal. It is considered that the Bulgarian experience (i.e. EB project) makes this cooperation easier economically. There are a few other main factors whose economic feasibility must still be considered in an industrial project.

Depreciation, carriage and handling fee

Annual depreciation charges can be estimated at 13 Euro/ton-fertilizer (based on table 1). The transportation fee and the handling fee were determined based on estimates obtained in an interview with Augusto Raposo Ltd. (Coimbra, 22 September 2005): transportation fee of 0.1 Euro/ton/km and handling fee of 2.0 Euro/ton.

Assuming that the obtained N-fertilizer is transported from Amarante thermal power station (the northern zone) to a consumer zone (e.g. a central zone such as Ribatejo, Alentejo, etc.), the transportation fee would be 20 Euro/ton/200km. Considering transportation, handling and depreciation (23 Euro/ton), the price of the by-product fertilizer for a consumer is estimated at 121 Euro/ton (627 Euro/ton as N). On the basis of this price, the WTP value is calculated again as follows (refer to formulas 14 and 15): WTP = Y\textsuperscript{1} - Y\textsuperscript{0} = [1 - (238/257)\textsuperscript{0.022}].11952 = 20 Euro. Multiplying 20 Euro/capita by 49,942 farmers (fertilizer beneficiaries) gives a total WTP of 998,840 Euro in the agricultural sector. The recalculated results indicate that the agricultural sector is willing to support 998,840 Euro for an SO\textsubscript{2} reduction project at a thermal power station and that 100% of the operating cost including annual depreciation can be covered by the agricultural sector's purchase of by-product fertilizer at 62.7 Euro/100kg-N in Portugal.

Market for N-fertilizer

The unit price of ammonium sulfate has varied between 85.2 and 65.0 Euro/100kg-N for the past 3 years in Portugal [32]. Thus, a Portuguese farmer can obtain by-product fertilizer that is cheaper than commercial fertilizer at current prices as compensation for financial support to the SO\textsubscript{2} reduction project at a thermal power station. The annual growth rate of N-fertilizer use worldwide has been about 8% since 1985 [33]. This global view also indicates the fertilizer market has been growing. As seen in formula (11), the smaller the ratio of P\textsubscript{1}/P\textsubscript{0} (the price of by-product fertilizer) to P\textsubscript{1}/P\textsubscript{0} (the present price of fertilizer), the greater the WTP value. Ammonium sulfate fertilizer costs US$160/ton (20.5% N) in the Eastern Corn Belt in the USA [34], and Danish farmers paid up to US$450/ton (20.5% N) in 1995 [5]. Such situation leads to a high value of P\textsubscript{1}/P\textsubscript{0}, and the value of P\textsubscript{1}/P\textsubscript{0} also gives a low value, which in turn gives a high great WTP value. From the money metric viewpoint, it can be considered that the agricultural sector has considerable willingness to support a project for making N-fertilizer from SO\textsubscript{2} flue gas at a thermal power station in countries where fertilizer is commonly used.

Link between agricultural sector and energy sector

The concept presented in this paper is not yet popular either in Portugal or in any other part of the world. Thermal power stations attempt to deal with the problem by installing air cleaning systems, and generally have no connection with agriculture, food production or fertilizers. This means that it is unlikely that a link will form naturally between an SO\textsubscript{2} emission source and fertilizer production. That is, an organizer is needed to link an air polluter (to
Table 1. Cost data for case study deduced from the Bulgarian experience

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit cost (Euro)</th>
<th>Annual amount</th>
<th>Annual cost (Euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator wage</td>
<td>1,000 × 3 operators/shift</td>
<td>4 shifts × 12</td>
<td>144,400</td>
</tr>
<tr>
<td>Maintenance (including general charge)</td>
<td>---</td>
<td>---</td>
<td>735,000</td>
</tr>
<tr>
<td>Water</td>
<td>0.015/ton</td>
<td>867,000 tons</td>
<td>13,200</td>
</tr>
<tr>
<td>Steam</td>
<td>2.5/ton</td>
<td>78,600 tons</td>
<td>196,500</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.08/kWh</td>
<td>34,000 MWh</td>
<td>2,720,000</td>
</tr>
<tr>
<td>Ammonia</td>
<td>150/ton</td>
<td>24,600 tons</td>
<td>3,690,000</td>
</tr>
</tbody>
</table>

Subtotal 7,499,100

By-product fertilizer 98,400 tons

Note: inlet SO₂ concentration = 1,800 ppm; inlet dust concentration = 800 mg/Nm³; inlet NOx concentration = 400 ppm; efficiency of SO₂ removal = 85% (target); NOx removal = 15% (reference); dust removal = 75% (reference); flow rate = 1,800,000 Nm³/h; flue gas temperature = 150°C; operation rate = 6,570 hours/year; construction cost = 35,000,000 Euro; and annual depreciation = 2,333,333 Euro.

Table 2. Statistical data on agriculture and fertilizer in Portugal

<table>
<thead>
<tr>
<th>Parameter (year)</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of farmers (1995)</td>
<td>445,200</td>
<td></td>
</tr>
<tr>
<td>Mean income (2000)</td>
<td>11,952</td>
<td>Euro/year/farmer</td>
</tr>
<tr>
<td>Total farmland (2003)</td>
<td>3,453,518</td>
<td>hectares</td>
</tr>
<tr>
<td>Expenditure on fertilizer (1995)</td>
<td>257</td>
<td>Euro/year/farmer</td>
</tr>
<tr>
<td>- N fertilizer (as N)</td>
<td>147</td>
<td>Euro/year/farmer</td>
</tr>
<tr>
<td>- P₂O₅ fertilizer</td>
<td>54</td>
<td>Euro/year/farmer</td>
</tr>
<tr>
<td>Consumption of fertilizer (1995)</td>
<td>0.38</td>
<td>tons/year/farmer</td>
</tr>
<tr>
<td>- N fertilizer (as N)</td>
<td>0.18</td>
<td>tons/year/farmer</td>
</tr>
<tr>
<td>- P₂O₅ fertilizer</td>
<td>0.16</td>
<td>tons/year/farmer</td>
</tr>
<tr>
<td>- K fertilizer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 1: Test plant using EB process at Maritsa East power plant
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Fig 2: Portugal’s import of N-fertilizer

Fig 3: Trend in FGD installation throughout the world

CONCLUSIONS

Using the Maritsa East project in Bulgaria as a reference, this paper presents the synthetic introduction to Amarante thermal power station (Portugal) of the EB process for converting air pollutants into N-fertilizer as a case study of an industrial project of mutual support between the agricultural sector and the energy sector. The agricultural sector would not likely suffer any economic damage, and this approach may help to reduce local air pollution and contain the outflow of local currency in countries where fertilizer is commonly used. Similar cases to that in Portugal can be expected in other regions such as the USA and Scandinavia. The explanation described here may not make a sufficient contribution to economic theory; however, this paper would seem to provide a new approach to fertilizer strategy and environmental tactics.

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