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

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ABSTRACT

A Bulgarian project at Maritsa East power station demonstrated the proper transformation of air pollutants (SO_x and NO_x) 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_x) 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_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_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_2, 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_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_x (SO_3 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_2) originating from electron beam irradiation oxidize SO_2 and SO_3 (and/or NO_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_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_x and NO_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^3N/h coal-fired flue gas (5,500 ppm SO_2, 140 ppm SO_3, 390ppm NO_x and 200 mg/m^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_x 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_x 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 λ (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:

$\partial V/\partial P_i = -\lambda x_i$ — (2) and $\partial V/\partial Y = \lambda$ (3)

Welfare change is estimated as WTP, where the WTP for change in a state vector Q = (p, Y) from Q^0 to Q^1 is defined by a curvilinear integral:

$$\Delta V = \int_{Q^0}^{Q^1} (\Sigma V_i dP_i + V_Y dY) \qquad (4)$$

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

$$\Delta V = \int_{Q^0}^{Q^1} [(\Sigma(-\lambda x_i)dP_i + \lambda dY] \qquad (5)$$

According to Samuelson's characterization [22]: $\lambda(p, Y) = \gamma(Y)$ (6). If the marginal utility of income is constant in formula (6): $\gamma(Y) = a/Y$ (7) where $a = \gamma(1)$. The utility function becomes homothetic, then formula (8) is true for a function ζ_i: $x_i(p, Y) = \zeta_i(p)Y$ (8)

Substituting formula (6) in (5), where $\gamma^0 = \gamma(Y^0)$:

$$\Delta V = -\gamma \int_{p^0}^{p^1} \Sigma x_i(p, Y^0)dP_i + \int_{Y^0}^{Y^1} \gamma(Y)dY \qquad (9)$$

Combining formulas (7), (8) and (9), where $\gamma^0 = \gamma(Y^0) = a/Y^0$ and $\gamma^0 = 1$ can be set by choosing a proper measure unit of γ^0 [23]:

$$\Delta V = -\gamma^0 \int_{p^0}^{p^1} \Sigma\zeta_i(p) \cdot Y^0 dP_i + \int_{Y^0}^{Y^1} a/YdY = -a\int_{p^0}^{p^1} \Sigma\zeta_i(p) \cdot dP_i + a \cdot \log Y^1/Y^0$$

(10)

$$\therefore \Delta V = \log Y^1/Y^0 - \alpha_1 \int_{p^0}^{p^1} 1/P_1 dP_1 = \log Y^1/Y^0 - \alpha_1 \cdot \log P_1^1/P_1^0$$

(11)

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_1^0 (present fertilizer) to P_1^1 (FGD by-product fertilizer), which is the economic merit; to obtain the by-product fertilizer, a farmer must invest an amount of Y^0-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); α_1 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 Nm^3/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 I that 98,400 tons/year of by-product fertilizer is produced by purifying 1,800,000 Nm^3/h SO_2 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 (α_1) 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_2 removal unit at a thermal power station. The values obtained in the section detailing case study data are substituted in formula (11) in order to calculate the farmer's WTP (i.e. Y^0-Y^1) toward the SO_2 removal project: P_1^0 = 257 Euro for current N-fertilizer (0.38 tons as N), P_1^1 = 150 Euro for by-product fertilizer (0.38 tons as N), and α_1 = 0.022 as the ratio of N-fertilizer expenditure/income.

Let $0 = \log(Y^1/Y^0) - \alpha_1 \cdot \log(P_1^1/P_1^0) = \log(Y^1/Y^0) - 0.022 \cdot \log(150/257)$ (12)

Then $Y^1/Y^0 = (0.584)^{0.022}$ (13)

$\therefore$ WTP = $Y^0 - Y^1 = [1 - (0.584)^{0.022}] \cdot 11952 = 141$ (14)

Multiplying 141 Euro/capita by 49,942 farmers (beneficiaries of by-product fertilizer) gives a total WTP of 7,041,822 Euro/year in the agricultural sector. 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_2 reduction project at a thermal power station and that 100% of the operating cost of this environment project can be covered by the agricultural sector's purchase of 98,400 tons of by-product fertilizer at 76 Euro/ton. Thus, a farmer can obtain by-product fertilizer that is cheaper than commercial fertilizer at current prices as compensation for financial support to the SO_2 reduction project at a thermal power station.

DISCUSSION

As has been discussed above, it is apparent that it would be advantageous for SO_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^1-Y^0 = $[1 - (238/257)^{0.022}] \cdot 11952 = 20$ 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_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_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_1^1 (the price of by-product fertilizer) to P_1^0 (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_1^0, and the value of P_1^1 is comparatively low; therefore, P_1^1/P_1^0 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_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_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

Parameter	Unit cost (Euro)	Annual amount	Annual cost (Euro)
Operator wage	1,000 × 3 operators/shift	4 shifts × 12	144,400
Maintenance	(including general charge)	---	735,000
Water	0.015/ton	867,000 tons	13,200
Steam	2.5/ton	78,600 tons	196,500
Electricity	0.08/kWh	34,000 MWh	2,720,000
Ammonia	150/ton	24,600 tons	3,690,000
Subtotal			7,499,100
By-product fertilizer		98,400 tons	

Note: inlet SO_2 concentration = 1,800 ppm; inlet dust concentration = 800 mg/Nm^3; inlet NOx concentration = 400 ppm; efficiency of SO_2 removal = 85% (target); NOx removal = 15% (reference); dust removal = 75% (reference); flow rate = 1,800,000 Nm^3/h; flue gas temperature = 150ºC; 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

Parameter (year)	Value	Unit
Number of farmers (1995)	445,200	
Mean income (2000)	11,952	Euro/year/farmer
Total farmland (2003)	3,453,518	hectares
Expenditure on fertilizer (1995)		
- N fertilizer (as N)	257	Euro/year/farmer
- P_2O_5 fertilizer	147	Euro/year/farmer
- K fertilizer	54	Euro/year/farmer
Consumption of fertilizer (1995)		
- N fertilizer (as N)	0.38	tons/year/farmer
- P_2O_5 fertilizer	0.18	tons/year/farmer
- K fertilizer	0.16	tons/year/farmer

Fig 1: Test plant using EB process at Maritsa East power plant

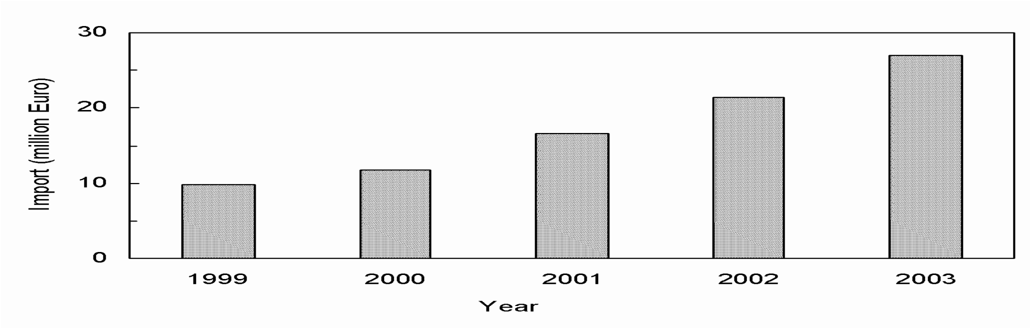

Fig 2: Portugal's import of N-fertilizer

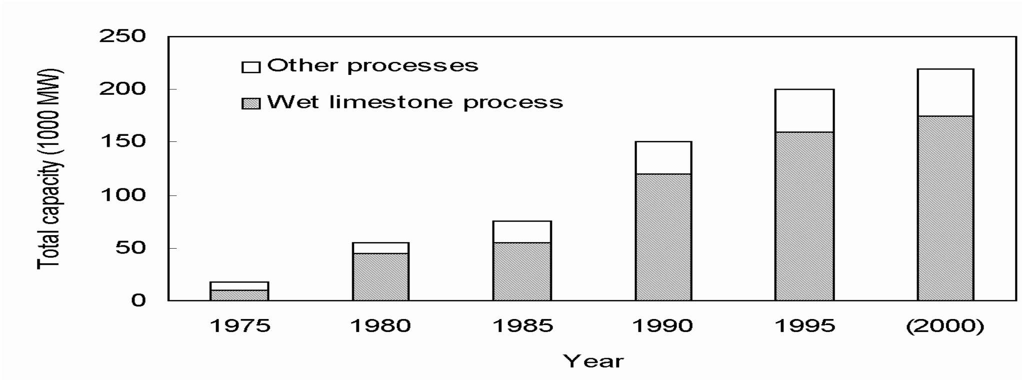

Fig 3: Trend in FGD installation throughout the world

put it differently, a producer of N-fertilizer once SO_2 has been processed) with a farmer (consumer of N-fertilizer). Furthermore, many people think that recycled material as an end product is expensive and inferior in quality. This may result from misunderstanding, prejudice or a narrow outlook. It is now proposed to link SO_2 reduction with N-fertilizer production by adopting the EB process at Svishtov thermal power station (312 MW) in Bulgaria. Obstacles lie in financial considerations as well as how to organize the link between the power station and the agricultural sector (or fertilizer sector).

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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