EXERGO- ECONOMIC ANALYSIS OF AIR POLLUTION FROM POWER PLANTS

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Abstract: The benefits of air pollution control techniques on a power plant are simulated with a scientifically based environmental model. Air pollution abatement techniques are assessed in terms of their resource cost (measured in dollars) and their effectiveness in reducing environmental damage (measured in dollars and healthy days lost). Which air pollution techniques are most efficient depend upon how much a day of health should be valued.

Keywords: environmental impact, cost of damage to human health, days of disability, emission control, flue gas flue gas desulfurization

1. INTRODUCTION

The evaluation of the environmental impact of power plants is traditionally based upon the assessment of the pollutant emissions, which have to comply with national and international limits. From a scientific point of view, not only human heath should be considered but also the depletion of resources and by-products.
This paper describes a comprehensive approach to introducing exergy-cost evaluations in the assessment of pollutant emissions.
The basic mathematic model
An economic balance can be built which allows the comparison of different options for the limitations of power plant emissions.

$$C_{en}^{el} = C_{tot}^{CI} + C_{tot}^{OM} + C_r + C_e \quad \left[\frac{\$}{\text{kWh}}\right] \tag{1}$$

C_{tot}^{CI} **-** the capital cost of the thermoenergetics system (include the cost of the basic system and the cost of the environmental system)

$$C_{tot}^{CI} = \sum_{C} \frac{C_c}{NE} + \sum_{C} \frac{C_M}{NE} \left[\frac{\$}{\text{kWh}}\right] \tag{2}$$

C_{tot}^{OM} - the service cost during plant operation (it's considered 10% of C_{tot}^{CI})
C_r – cost of the direct consumption of primary resources in the production process. This obviously includes fuel, but can be generalized to water, lubrificants, solids (e.g., limestone or lime for emission treatment)

$$C_r = \sum_r c_r m_r e_r \left[\frac{\$}{\mathrm{kWh}}\right] \tag{3}$$

C_e – cost of environmental

$$C_e = C_{ef\,n}^{S} + C_d^{PI} \left[\frac{\$}{\mathrm{kWh}}\right] \tag{4}$$

This cost include:

$C_{ef\,n}^{S}$ - cost of damage to human health. In cases of extreme pollution or continuous exposure to pollutant emissions, sufficient clinical data exist for some major pollutants about the effects on human health. These data are expressed as equivalence days of disability or hospitalisation. A monetary cost can then be applied.

$$C_{ef\,n}^{S} = \sum_h \sum_k m_k z_{hk} c_h e_h \left[\frac{\$}{\mathrm{kWh}}\right] \tag{5}$$

C_d^{PI} - cost of the destruction of intermediate products by the emissions. Intermediate products are typically produced by human activities, and have typically higher prices than natural resources, as a production cycle is involved for their manufacture. Typically, this term can account for corrosion damage of metal surface; repainting; damage to plants and agriculture; attack to construction materials. Too, damages to animals such as cattle, fish, etc can be accounted here. Also, monuments can be considered as human products of very high added value, so that the damage to the artistic environmental can also be accounted by this term.

$$C_d^{PI} = \sum_s \sum_k m_k y_{sk} e_k \left[\frac{\$}{\mathrm{kWh}}\right] \tag{6}$$

2. APPLICATION TO A SIMPLIFIED TEST-CASE

The advanced thermodynamics approach to the evaluation of the environmental impact of energy production is applied to a reference power plant of 1000 MWe capacity. In this application, the study is limited to the emission of SO_2 and its obnoxious effects on human health. The reference case considered is a power plant burning high sulphur coal. Three different power plant configurations are compared:

1. power plant burning coal without SO_2 removal system
2. power plant operating with wet flue gas desulphurisation (FGD) system
3. power plant burning the same coal with a fluidised bed combustor

Power plant main characteristics. Table 1

Net power output	MW, kWh/an	1000, 7884*10^6
Net power plant thermal Efficiency - without SO_2 removal system - with wet flue gas desulphurisation - with a fluidised bed combustor	 % % %	 38 37 38
Operating conditions	hours/year	8760
Capacity factor	%	90
Power plant operating life time	years	25
Power plant capital cost - without SO_2 removal system - with wet flue gas desulphurisation - with a fluidised bed combustor	$/kW inst	 780 940 1100

Coal analysis. Table 2

C^i	77,16 %
O^i_2	11,12 %
N^i_2	1,39 %
H^i_2	6,04 %
S^i	4,29 %
Q_i [kJ/kg]	31877
$e_{carbune}$ [kJ/kg]	34461

2.1. THE MATHEMATICAL MODEL OF POWER PLANT WITHOUT SO_2 REMOVAL SYSTEM

The 1000 Mwe generating power plant requires a thermal power input of approximately 2630 MWt, corresponding to a coal consumption of about 82,5 kg/s. The SO_2 mass flow rate can be determined:

$$\dot{m}_{SO_2} = B \cdot \frac{M_{SO_2}}{M_S} \cdot S^i = 82{,}5 \cdot \frac{64}{32} \cdot 0{,}0429 = 7{,}08 \left[\frac{kg\ SO_2}{s}\right] \tag{7}$$

$$C_{tot}^{CI} = \frac{C_c}{N \cdot E} = 0{,}00729 \left[\frac{\$}{\text{kWh}}\right] \tag{8}$$

$$C_{tot}^{OM} = 0{,}000729 \left[\frac{\$}{\text{kWh}}\right]$$

The cost of the coal consumption (assuming coal cost of about 53$/tons) is:

$$C_r = 0{,}01637 \left[\frac{\$}{\text{kWh}}\right]$$

The cost of damage to human health includes both the social impacts due to SO_2 emissions and the social impact due to coal mining. The method applied to calculation of reference unit cost of one day of human disability and of one fatality is describes in [1].

$$C_e = C_{ef\,n}^{S} \left[\frac{\$}{\text{kWh}}\right] \tag{9}$$

$$C_d = 159\$/\text{dis, day}$$

$$C_f = 430484\,\$/\text{fat, day}$$

$$z_{dis,\,SO2} = 0{,}0813 \text{ x } 10^{-6} \text{ dis/kJ } SO_2$$

$$z_{fat,\,SO2} = 0{,}0107 \text{ x } 10^{-9} \text{ fat/ kJ } SO_2$$

$$z_{dis,carbune} = 0{,}0692 \cdot 10^{-9} \text{ dis/ kJ coal}$$

$$z_{fat,carbune} = 0{,}0375 \cdot 10^{-12} \text{ fat/ kJ coal}$$

$$e^*_{SO_2} = 303500 \frac{kJ}{kmol} \text{ [2]}$$

$$C_e = \sum_h \sum_k m_k z_{hk} c_h \cdot e_h = 0{,}0024 \left[\frac{\$}{kWh}\right]$$

The cost of electrical energy is:

$$C_{en}^{el} = 0{,}02537 \left[\frac{\$}{\text{kWh}}\right]$$

2.2. THE MATHEMATICAL MODEL OF POWER PLANT WITH WET WET DESULPHURISATION SYSTEM

The FGD system is characterized by a SO_2 removal efficiency of about 94% and Ca/S = 1. The FGD plant causes an increase in power plant capital cost of about 160 $/kW. The power plant efficiency is reduced of 1 %.

$$C_{tot}^{CI} = \sum_C \frac{C_c}{NE} + \sum_C \frac{C_M}{NE} = 0{,}008077\left[\frac{\$}{kWh}\right] \tag{10}$$

$$C_{tot}^{OM} = 0{,}0008077\left[\frac{\$}{\text{kWh}}\right]$$

The resource cot includes the cost of coal and limestone consumption, assuming a cost of about 50 $/tons.

$$m_{CaCO_3} = 0{,}042 \frac{kg}{kWh}$$

$$c_{CaCO_3} = 0{,}21 \cdot 10^{-6} \frac{\$}{\text{kJ}}$$

$$e^*{}_{CaCO_3} = 5050 \frac{kJ}{kmol} \text{ [2]}$$

$$\Rightarrow x_{CaCO_3} = \frac{e_{CaCO_3}}{M_{CaCO_3}} = 50{,}5\left[\frac{kJ}{kg}\right] \tag{11}$$

$$C_r = \left(C_{coal} \cdot m_{coal} \cdot x_{coal}\right) + \left(C_{CaCO_3} \cdot m_{CaCO_3} \cdot x_{CaCO_3}\right) = 0{,}0167 \frac{\$}{\text{kWh}} \tag{12}$$

The environmental cost includes the following impacts: SO_2 emissions, coal mining and limestone quarring.

$$z_{dis\,CaCO_3} = 0{,}0472 \cdot 10^{-6}\, dis / kJ_{\,CaCO_3}$$

$$z_{fat\,CaCO_3} = 0{,}0256 \cdot 10^{-9}\, fat / kJ_{\,CaCO_3}$$

$$C_e = m_{SO_2} \cdot x_{SO_2} \cdot \left(z_{dis\,SO_2} \cdot C_d + z_{fat\,SO_2} \cdot C_f\right) + m_{coal} \cdot x_{coal} \cdot \left(z_{dis\ coal} \cdot C_d + z_{fat\ coal} \cdot C_f\right)$$
$$+ m_{CaCO_3} \cdot x_{CaCO_3} \cdot \left(z_{dis,CaCO_3} \cdot C_d + z_{fat\,CaCO_3} \cdot C_f\right) = 0{,}000457 \frac{\$}{\text{kWh}} \qquad (III.49) \tag{13}$$

The cost of electrical energy is:

$$C_{en}^{el} = 0{,}0260417\left[\frac{\$}{\text{kWh}}\right]$$

2.3. THE MATHEMATICAL MODEL OF POWER PLANT WITH FLUIDIZED BED COMBUSTOR

When a fluidized bed combustor is used, limestone is assumed to be used in the fluidized bed in the ratio Ca/S =3, allowing an SO_2 removal efficiency of about 92%.

$$C_{tot}^{CI} = \frac{C_c}{N \cdot E} = 0{,}01021\frac{\$}{\text{kWh}} \tag{14}$$

$$C_{tot}^{OM} = 0{,}001021\left[\frac{\$}{\text{kWh}}\right] \tag{15}$$

$$C_r = \left(C_{coal} \cdot m_{coal} \cdot x_{coal}\right) + \left(C_{CaCO_3} \cdot m_{CaCO_3} \cdot x_{CaCO_3}\right) = 0{,}0211\left[\frac{\$}{\text{kWh}}\right]$$

$$\begin{aligned} C_e = C_{ef\,n}^{s} &= m_{SO_2} \cdot x_{SO_2} \cdot \left(z_{dis\,SO_2} \cdot C_d + z_{fat\,SO_2} \cdot C_f\right) + m_{coal} \cdot x_{coal} \cdot \left(z_{dis\,coal} \cdot C_d + z_{fat\,coal} \cdot C_f\right) \\ &+ m_{CaCO_3} \cdot x_{CaCO_3} \cdot \left(z_{dis\,CaCO_3} \cdot C_d + z_{fat\,CaCO_3} \cdot C_f\right) = 0{,}000534\frac{\$}{\text{kWh}} \end{aligned} \tag{16}$$

The cost of electrical energy is:

$$C_{en}^{el} = 0{,}03184\frac{\$}{\text{kWh}}$$

All the costs obtained for the three cases are collected in table 3 and compared in figure 1.

Table 3.

Generating power plant configuration	Cost of coal ($/kWh)	Cost of limestone ($/kWh)	Capital cost ($/kWh)	Cost of damage to human health ($/kWh)	Cost of electrical energy ($/kWh)
without SO_2 removal system	0,01637	-	0,00729	0,0024	0,02537
with wet flue gas desulphurisation	0,0168	$0{,}44541\text{x}10^{-6}$	0,008077	0,000457	0,0277
- with a fluidised bed combustor	0,0163	0,00473	0,01021	0,000534	0,03184

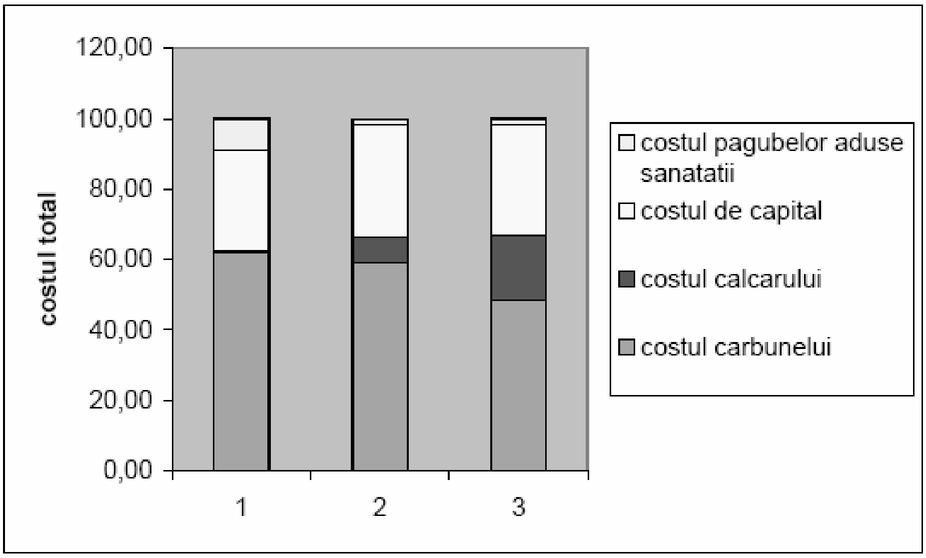

Fig. 1 Cost of electrical energy

4. CONCLUSION

The paper presents an advanced thermodynamics approach to the evaluation of the environmental impact of energy production by power plants. The method is based upon the evaluation of the exergy of the pollutant emissions and take into account the effects on human health and generally the environmental impact.

LIST OF SYMBOLS:

C_{en}^{el} - cost of electric energy produced by the thermoenergetics system

C_{tot}^{CI} **-** the capital cost of the thermoenergetics system (include the cost of the basic system and the cost of the environmental system)

C_c – the capital cost of the basic energetic system [$]

C_M - the capital cost of the environmental energetic system [$]

N – number of years of projected life of the plant

E – average amount of energy produced by the plant in one year of operation [kWh/an]

C_{tot}^{OM} - the service cost during plant operation

C_r – cost of the direct consumption of primary resources in the production process

c_r – cost of the unit of exergy of the r-th natural resource

m_r – mass flowrate of the r-th natural resource per unit of final production

e_r – specific exergy of the r-th natural resource

C_e – cost of environmental

$C_{ef\,n}^{S}$ - cost of damage to human health

m_k – mass flowrate of the k-th emission

z_{hk} – amount of units of human disability per unit of exergy of the k-th emission

c_h – reference unit cost of the human disability

e_k – specific exergy of the k-th emission

C_d^{PI} - cost of the destruction of intermediate products by the emissions

m_k – mass flowrate of the k-th emission
y_{sk} – cost of the s-th public good or intermediate product destroyed per unit exergy of the k-th emission
e_k – specific exergy of the k-th emission

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