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A Carbon Exergy Tax Evaluation Based on the Efficient Use of Energy Resources: A Case Study

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Abstract

An instrument to promote the CO_2 emission reductions, taking the Kyoto Protocol goal into account, can be the assignment to energy conversion plants of a monetary charge linked to their specific emission intensity. Once the choice of a charge is defined, the next problem is the choice of a strategy to determine the amount of the imposed charge, named Carbon Tax (CT).

In this paper an analytical procedure for the Carbon Tax evaluation is proposed and applied. This approach is based on the concept of *Efficiency Penalty* of the energy system, that represents the evaluation of the cost of the exergy destroyed inside the system and the cost of the exergy rejected in the biosphere with the plant wastes; the *Efficiency Penalty* term is coupled with the evaluation of the *Index of CO_2 Emission*, which connects the amount of the CO_2 emitted by the plant with the Second Law efficiency of the plant itself. The evaluated charge on the CO_2 emissions is defined as *Carbon Exergy Tax* (*CET*). The procedure is applied here to the analysis of a 700 MW combined plant burning fossil fuels in two different configurations: a typical natural gas fired combined plant, and a coal fired combined plant burning coal in a Pressurised Fluidised Bed Combustor (PFBC).

Key words: Environomic Optimization, Efficiency Penalty, CO_2 emissions, Carbon Tax, Carbon Exergy Tax

1. Introduction

In the energy systems field, one of the most important problems is the evaluation and management of pollutant emissions connected to energy conversion activities in energy plants such as power plants.

The environmental problem of the energy systems is connected mainly to the emission of pollutants such as UHC (unburned hydro-carbons), CO, NO_x, SO_x, and CO_2.

There are two main approaches to face the environmental problem of energy systems:

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1. *Regulatory approach*: imposition, by law, of the utilization of pollutant abatement devices, in order to reduce the emission in atmosphere of pollutant substances with the exhaust gases.
2. *Economic approach*: imposition of economic charges to the pollutant substances, in order to force their producer (the energy system) to reduce their emission in atmosphere; the charges are imposed by a public administration.

In general, the imposition of economic charges to the pollutant substances has the aim, and especially the effect, of forcing the adoption of abatement devices by the energy systems. The utilization of abatement devices depends on the relative amount of the costs of the devices and of the economic charges imposed by the local administration where the energy system operates. In general, the cost of the abatement devices are very high, and their utilization must therefore be forced with the taxation of the pollutant emissions. In this sense, the regulatory approach and the economic approach have the same aim, to force the adoption of abatement devices by law instruments.

The economic approach is based on political considerations, taking into account the danger of each pollutant and the cost that the society decides to assign to this danger; this approach depends therefore on the characteristics of each pollutant substance.

It is interesting to develop a short description and discussion about the two environmental saving approaches. As far as UHC, CO, NO_x and SO_x emissions are concerned, they represent toxic pollutants and a direct and demonstrated danger for the human health; the widely accepted approach is therefore the adoption of abatement devices (Agazzani, 1997; Rizk and Mongia, 1993; Agazzani et al., 1998; Richter and al., 1984) to reduce their emitted mass flows under the limits sufficient to minimize health hazards. A fine is used to punish the energy systems that emits the pollutant substances in quantities larger than that allowed by law. The second approach, relevant for CO_2 emissions is discussed in the following subsection.

1.1 Regulatory approach: forcing of the adoption of pollutant abatement devices

The CO_2 emissions represent a serious environmental problem, connected to the greenhouse effect (Boubel et al., 1994). A technical approach to face the problem is to invest in CO_2 sequestration. As far as recovery techniques are concerned, the principal ones are membrane separation and amine absorption (Corti et al., 1998; Langeland and Wilhelmsen, 1993; Iijima et al., 1998); as far as disposal options are concerned, the principal ones are deep ocean disposal, aqueous solution disposal and depleted gas-field disposal. The separated CO_2 must be compressed before being transported to the disposal area (requiring power). These energy requirements determine a decrease of the efficiency. This reduction has been evaluated in literature approximately in the order of 3 to 5 percentage points of the power production, but in some cases, it can reach the value of 10 points, as suggested by Iijima, Mitsuoka, Mimura and Suda (1998).

The estimated investment costs for CO_2 sequestration and disposal are very high since the recovery equipment is expensive and the CO_2 flow rate is usually high (Summerfield et al., 1993). However, the most difficult aspect is the evaluation of disposal costs: the pipeline cost to transport the CO_2 to the disposal area and the injection costs. Furthermore, if the recovery costs can be determined using a detailed economic approach, the disposal costs are very difficult to be generalised: they in fact depend entirely on the particular case under examination and especially on the location of the power plant with respect to the disposal area (Skovholt, 1993). In literature (Corti et al., 1998; Langeland and Wilhelmsen, 1993; Iijima et al., 1998), the CO_2 sequestration costs have been estimated to affect the capital costs of the plant by around 75 %, and an even larger percentage has been suggested by Langeland and Wilhelmsen (1993), Summerfield, Goldthorpe, Williams and Sheikh (1993).

1.2 Economic approach

In the economic theory, the problems induced on the environment by the CO_2 pollutant emissions, and the related costs, are external costs of the energy systems. The economic approach has to decide how to estimate the external costs of pollutant emissions and how to internalise them into the economic evaluation of the system (Goodstein, 1999; Frangopoulos, 1991; Frangopoulos and von Spakovsky, 1993; Frangopoulos and Caralis, 1997; Exergia, 1998; Gaivao and Jaumotte, 1985; Faber and Wagenhals, 1988; Parkin et al., 1997; Ottinger et al., 1990; OECD, 1994; Boubel et al., 1994). As far as the problem of estimation of external pollution costs is concerned, the most used approaches proposed in literature are:

- Direct methods: a *damage cost* is defined, to represent the cost to be paid to repair environmental damage.

- Proxy methods: an *avoidance cost* is defined, to represent the cost of avoiding environmental damage.

As far as the problem of internalization of pollution externalities is concerned, the most used approaches are *market-based*; in this procedure a cost is associated to the pollutant activities and assigned to the energy systems (the regulation represents a form of market-based approach, as pollution penalties are usually monetary). There are two main market-based approaches proposed in literature:

- Charges: these represent taxes assigned to the pollutants emitted by the energy system.
- Market-creation of pollution permits: these are allowances, released by the regulatory authority, to pollute a finite quantity of substances; a fixed number of permits to pollute are issued and sold to the energy systems, and they can be traded between the systems.

The charge approach, the easiest and most direct way of internalising pollution externalities, is the most commonly used approach.

1.3 Discussion about the environmental saving approaches

It is under evaluation the idea that the increase of the CO_2 concentration determines an atmosphere temperature rise (Boubel et al., 1994); nevertheless it is not toxic and moreover it is inevitably emitted in large quantities during the hydrocarbon combustion processes. The costs of the sequestration devices are very high, and they can vary largely in each particular case. Considering these characteristics, it could be very difficult to impose the adoption of CO_2 sequestration devices, in particular in the developing countries, whose energy transformation technology is based, and will be also in the future, on the burning of fossil fuels. In the case of CO_2, it is therefore of great interest the economic approach of imposing a tax to the pollutant emissions in order to obtain an environment saving. In many countries a tax related to CO_2 emission (Carbon Tax, CT) has been introduced or is under discussion. This charge frequently becomes a surcharge imposed on the fuel costs (Legge Finanziaria Italiana, 1999), and usually signals the marginal damage suffered by the society due to the pollution emitted by the plant.

This type of charge is applied directly to the energy production activity which uses hydrocarbon fuels: in fact, the CO_2 emissions are inevitably associated with this energy transformation activity. Maybe, it could be preferable that the possible charges would be imposed not to the energy production activities, but to the *inefficient* ones. The charge must not be imposed directly on the hydrocarbon fuel, but on its *inefficient use*.

Leaving to the political decision maker the choice of the level of taxation of the CO_2 released in atmosphere, a possible complementary approach could be that of operating on the causes of CO_2 production: to punish the inefficient use of scarce energy resources that determines a larger emission of CO_2 than an efficient use. It has been discussed by Santarelli (1998, 1999a) a procedure of *Environomic Optimization* of energy systems which takes into account the costs connected with the inefficient utilization of energy resources by the systems. These costs are evaluated assigning a cost to the exergy destroyed inside the system and to the exergy rejected into the biosphere with the plant wastes. The aim of the imposition of a cost to the exergy destroyed and the exergy rejected is to reward an efficient use of energy resources, to prevent pollutant emissions of CO_2 as much as possible. In this sense this optimization approach is connected to environment protection. In the procedure, the costs assigned to the exergy destroyed inside the system and to the exergy rejected into the biosphere with the plant wastes have been defined as *Efficiency Penalty*.

In a previous paper (Borchiellini et al., 2000) this penalty has been used to develop an analytical procedure to determine the values of the proposed concept of *Carbon Exergy Tax* (*CET*) (Massardo et al., 2000) imposed to the produced CO_2. The *Efficiency Penalty* term is coupled with the evaluation of the *Index of CO_2 Emission*, which connects the amount of the CO_2 emitted by the plant with the Second Law efficiency of the plant itself. In this way the procedure allows a cost to the emitted CO_2 based on plant efficiency to be assigned.

The use of the *Efficiency Penalty* does not represent an evaluation of the environmental externalities, such as the *damage* or *avoidance costs*, but it represents a different point of view, which underlines the importance of the efficient utilization of energy resources inside the plants, in an environmental perspective.

In this paper, the analytical procedure of *CET* evaluation is applied to a case study represented by a 700 MW combined plant burning fossil fuels. It is analysed in two different configurations (a typical natural gas fired combined plant, and a coal fired combined plant burning coal in a pressurised fluidised bed combustor), in order to analyse the results obtained by the procedure applied to the same plant burning fossil fuels with different economic cost and different environmental performance. The values of the CO_2 emissions charges obtained with the proposed procedure are presented and discussed in depth, and compared to the possible costs of CO_2 sequestration activities for this typology of plant.

2. Environomic Optimisation and CO_2 Influence

The *Environomic Optimisation* of an energy system comes from the *Thermoeconomic Optimisation* problem, represented by a non-linear programming (NLP) Problem with equality and inequality constraints (Agazzani, 1997; Santarelli, 1998; Santarelli et al., 1999a):

$$\min_{x} F_1(x) = \min_{x}\{Z_I(x) + C_f(x) + Z_A(x) + C_r(x)\} \quad (1)$$

subjected to the constraints $h_j(\mathbf{x})=0;\ g_k(\mathbf{x})\leq 0$

where **x** is the decision variables vector, Z_a represents the capital cost of the pollution abatement components adopted by the system, and C_r represents the cost of resources utilized by the pollution abatement components (e.g. water and limestone, ammonia, etc.).

The *Environomic Optimisation* is an extension of the optimization problem (1), to take into account also the economic role of environmental pollution (Frangopoulos and von Spakovsky, 1993):

$$\min_{x} F_2(x) = \min_{x}\{F_1(x) + C_P(x)\} \quad (2)$$

subjected to the constraints $h_j(\mathbf{x})=0;\ g_k(\mathbf{x})\leq 0$

where C_p is the cost linked to pollution of the environment (usually in the form of political taxes applied to the unit mass of pollutant).

The environomic optimization represents a powerful instrument to analyse the effects of the adoption of the environmental saving procedures (Technical and Economic Approaches) on the determination of the optimum operation point of the system and on its economic behaviour. In fact, the environomic optimization has been used in a previous paper (Santarelli et al., 1999b) in order to optimise different energy systems taking into account the costs of the abatement devices for reduction of SO_x and NO_x, and in particular the role of CT and of CO_2 sequestration devices costs on the economic evaluation of the systems. In equation (2), the CT is considered in the second term of the right hand side, and the CO_2 sequestration devices costs in the first one (that is, in the third and fourth ones of Eq. (1). The aim was to evaluate the order of magnitude of CT relative to various scenarios of CO_2 sequestration devices costs: it has been developed a comparison between different scenarios of CT and cost of CO_2 sequestration activities, in order to determine the break-even values of CT face to the cost of sequestration. This procedure corresponds to the economic one of equating the cost of pollution control (the cost of CO_2 sequestration activities) with the marginal damage suffered by the society (evaluated with different procedures by research groups of economists, physicists, doctors: see for example Ottinger et al., 1990; OECD, 1994; Boubel et al., 1994) indicated by the imposed CT. The results of the analysis can be found in Santarelli et al. (1999b), and also at the end of this paper.

While the CO_2 sequestration costs can be evaluated with the same procedure used for the capital costs, the CT is usually imposed by the public administrations. Moreover, in many cases it is imposed as an increase of the fuel cost (such as a tax on the fuel of Legge Finanziaria Italiana 1999), not considering the way in which the fuel is used by each energy system. But, as analysed in (Borchiellini et al., 2000; Massardo et al., 2000), an approach to the CT evaluation that does not consider the role of the efficient utilization of energy resources presents some limits. To make an example, let us consider the case of a generic plant (*a*) which is much more efficient than the plant (*b*), and which therefore develops a better utilization of energy resources to obtain, by hypothesis, the same energy output: is it equitable to treat the two plants, from the taxation of the CO_2 emissions point of view, in the same way? Does this position represent an incentive for the efficient use of energy resources (even if the plant (*a*) already spares in the fuel cost due to the better efficiency)? A possible answer to the aforementioned questions has been advanced in (Borchiellini et al., 2000; Massardo et al., 2000), and will be summarised in the following.

3. The Analytical Procedure for a *Carbon Exergy Tax* (*CET*) Evaluation Based on the Efficient Utilization of Energy Resources

The aim pursued by the analytical procedure for *Carbon Exergy Tax* (*CET*) evaluation is to assign a cost to the emission of CO_2 that is based only on thermoeconomic considerations (Borchiellini et al., 2000; Massardo et al., 2000) that are objective, as they are based on thermodynamic concepts, and the economic costs of components and fuels are data coming from the market. A cost linked to the operation inefficiencies of the plant, inefficiencies which determine a larger amount of pollutant emissions linked to the larger fuel consumption, is here considered.

First of all, it is considered an evolution of the environomic objective function (2), leading to the following objective function proposed in Santarelli (1998) and Santarelli et al., 1999a:

$$\min_x F_3(x) = \min_x \{F_1(x) + C_{irr}(x) + C_w(x)\} \qquad (3)$$

subjected to the constraints $h_j(\mathbf{x})=0;\ g_k(\mathbf{x})\leq 0$

In the proposed environomic objective function (3), C_{irr} and C_w represent the costs linked to operation inefficiencies, and their sum is named *Efficiency Penalty*. The *Efficiency Penalty* term substitutes the role of the term C_p of (2) (the environmental cost of CO_2 or CT): instead to punish the emission of CO_2, the aim is to operate on the system inefficiencies, one of the most important causes of pollution. The methodologies is based on the Thermoeconomic procedures, and they work very well in particular with multiple-product systems; therefore the proposed methodology is general and can be applied to every system typology. The meaning of the *Efficiency Penalty*, linked to environmental considerations, is illustrated in the following.

Cost of destroyed exergy

The term of the objective function related to the cost of the destroyed exergy is:

$$C_{irr}(x) = \sum_{i=1}^{N_{components}} c_{e_i} [\Psi_e(x) - \Psi_o(x)]_i \qquad (4)$$

In order to assign a weight to the irreversibilities corresponding to their relevance in terms of resource waste, the unit efficiency penalty c_e of a unit of irreversibility produced by a component i is calculated by the product of the economic fuel cost of the system (e.g. cost of natural gas) and the Unit Exergetic Cost (*UEC*) of the exergy input flow of the same component:

$$c_{e_i} = c_f \cdot UEC_i(x) \qquad (5)$$

The *UECs* of the system flows are calculated via a Thermoeconomic Analysis of the system. The *UECs* determine the exergetic importance of each flow of the system. The concept of Thermoeconomic Analysis and of *UECs* is well explained in (Lozano and Valero, 1993; Arena et al., 1997), and summarised in (Borchiellini et al., 2000).

The *UECs* of all system exergy flows are determined, in the operation point, through the Thermoeconomic Analysis of the system, and consequently the unit efficiency penalty of the irreversibilities of the system are determined.

Residual exergy cost

The residual exergy cost term is related to the exergy rejected into the biosphere with pollutant emissions and is given by:

$$C_w(x) = \sum_{r=1}^{N_{wastes}} c_w \Psi_w(x) \qquad (6)$$

A unit efficiency penalty c_r must be assigned to the residual exergy. If one refers to the pollutant emissions of classical energy systems only, the residual exergy is that which is connected to the exhaust gases and is given by (Bejan et al.,1996; Kotas, 1985).

As far as the residual exergy *UEC* is concerned, it is here assimilated to the *UEC* of the product of the system, as the residual exergy is considered to be a potential product which is wasted:

$$c_w = c_f \cdot UEC_p(x) \qquad (7)$$

If the system has more than one product, the more expensive one is considered, that is, the one with the highest *UEC* value (Santarelli, 1998; Santarelli et al., 1999a); this choice is independent from the production purpose of the plant, as the aim of the procedure is to penalise the more is possible the waste of residual exergy.

The cost of destroyed exergy (4) and the cost of residual exergy (6) of the plant, that is the *Efficiency Penalty* Π_ε:

$$\Pi_\varepsilon(x) = 3600 \cdot N \cdot \{C_{irr}(x) + C_w(x)\} \qquad (8)$$

represents the basis of the charges imposed to the plant for the CO_2 emissions. To determine the amount of the charges it is necessary to consider also another element.

Index of CO_2 Emission

It has to be taken also the quantity of CO_2 emitted by the plant into account. The idea is not to consider the absolute value of the CO_2 emitted by the plant, but to relate it to the exergy production of the plant itself, to take into account its environmental effectiveness compared to its exergy production. Therefore, the idea is to introduce an *Index of CO_2 Emission*: the aim is to express this index as a non dimensional number, and therefore it is defined as:

$$I^*_{CO_2} = \frac{I_{CO_2}}{I_{CO_2rif}} = \frac{\dfrac{G_{CO_2}}{\Psi_p}}{1} \quad \frac{\dfrac{kg/s}{kWh/s}}{kg/kWh} \qquad (9)$$

where I^*_{CO2} is the *Index of CO_2 Emission*, and it is equal to I_{CO2} if it is made the imposition:

Reference Index of CO_2 Emission

I_{CO2rif} = 1 [kg_{CO2} / kWh]

With this definition, the *Index of CO_2 Emission* is a non dimensional number.

By means of this index, it is possible to consider the emitted CO_2 in relation with global exergy power Ψ_p. The larger I^*_{CO2} is, the larger is the environmental impact of the plant due to CO_2. The expression of the index is developed in the Appendix.

The *Index of CO_2 Emission* is used with the *Efficiency Penalty* to evaluate the amount of the charge imposed to the CO_2 emitted by the plant:

$$C_{CO_2} = I^*_{CO_2} \cdot \Pi_\varepsilon \qquad (10)$$

The expression (10) is developed in the Appendix; the result is the following expression:

$$C_{CO_2} \propto \frac{[C] \cdot G_f \cdot (\Psi_{irr} + \Psi_w)}{LHV \cdot G_f - (\Psi_{irr} + \Psi_w)} \qquad (11)$$

In this expression, the functional relations are.

a) relations with plant efficiency:

- if (Ψ_{irr}+ Ψ_w) increases, C_{CO2} increases;
- if G_f increases with constant (Ψ_{irr}+ Ψ_w), that is, with increasing energy production, C_{CO2} decreases because in this case plant efficiency increases;

b) relations with fuel quality:

- if [*C*] increases, C_{CO2} increases;
- if *LHV* increases, C_{CO2} decreases.

The *CO_2-Charge* values are affected by the fuel cost: in fact, the cost of the destroyed exergy c_e and of the residual exergy c_w are proportional to the fuel cost, because the destruction and loss of exergy is equal to destruction of primary fuel. The methodology therefore links the cost per unit ton of CO_2 to the fuel cost: if the fuel cost increases, then does the cost per unit of CO_2. In a perspective of charges imposed to the efficiency, if the fuel cost increases, then the cost of the exergy destruction increases too. In practice, in an economic scenario of increasing costs, also the sequestration costs are forced to increase, and therefore it could be correct an increase of CO_2 charges. Besides that, this procedure encourages the efficient utilization of the more valuable fuels.

The “induced” CO_2 emissions (linked to the plant construction, the fuel extraction, etc) have not been considered in this paper, but the same methodology could be applied to the various activities connected to the energy plant construction and to the primary fuel extraction.

The resulting cost per unit ton of CO_2 emitted is the concept of *CET*:

$$CET = \frac{C_{CO_2}}{G_{CO_2}} \quad \frac{\$/yr}{ton/yr} = I^*_{CO_2} \cdot \frac{\Pi_\varepsilon}{G_{CO_2}} \quad \frac{\$/yr}{ton/yr} \qquad (12)$$

The expression of the *CET* is developed in the Appendix.

To evaluate the effect of the imposition of the *CET* to the cost of the electricity produced by the plant, it is considered the concept of $c_{el,CET}$, the absolute increase of electricity cost due to the imposition of *CET* expressed in c$/kWh:

$$c_{el,CET} = \frac{CET \cdot G_{CO_2} \cdot N \cdot 3.6}{W_{el} \cdot N} \quad \frac{c\$/yr}{kWh/yr} \qquad (13)$$

It is considered also the concept of $\Delta c_{el,CET}$, the percentage increase of the electricity cost respect its original cost without the imposition of *CET*:

$$\Delta c_{el,CET} = \frac{c_{el,CET}}{c_{el}} \cdot 100 \qquad (14)$$

These concepts are useful to understand the impact on the electricity product cost due to the imposition of the *CET* on the unit ton of emitted CO_2.

After the considerations made, it is possible to redefine the objective function (3) of the environomic optimization problem in the form that takes the *Index of CO_2 Emission* into account, using a charge on the CO_2 emissions (*CET*) based on an analytical procedure (Borchiellini et al., 2000; Massardo et al., 2000):

$$\min_x F_4(x) = \min_x \left\{ F_1(x) + I^*_{CO_2} \cdot C_{irr}(x) + I^*_{CO_2} \cdot C_w(x) \right\} \qquad (15)$$

subjected to the constraints $h_j(\mathbf{x})=0;\ g_k(\mathbf{x})\leq 0$

This objective function will be used to determine the operation points of the plants considered in the case study.

4. Case Study

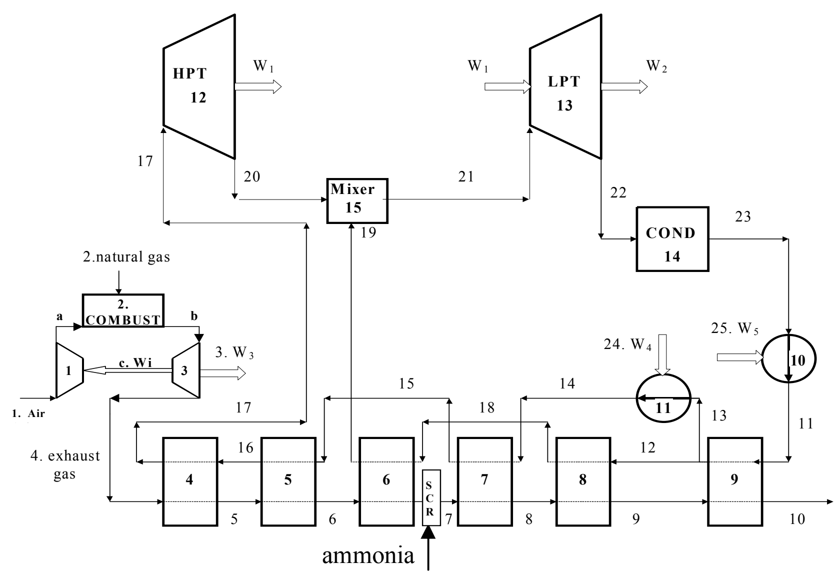
The described analytical procedure for the evaluation of the *CET* will be applied to a case study represented by a 700 MW combined plant burning fossil fuels. Two different configurations have been analysed: 1) a typical natural gas fired combined plant; 2) a coal fired combined plant burning coal in a PFBC (Pressurised Fluidised Bed Combustor). This is made with the aim of analysing the results obtained by the procedure applied to the similar plant burning fossil fuels with different cost and environmental performances.

Concerning the utilization of coal as fuel in a combined cycle plant, it is well known that the attention at present time is dedicated to the integration of a coal gasification process with combined plant, obtaining the IGCC plant. This solution represents the more efficient and environmental friendly approach, but it requires the integration of the gasification devices (such as pressure vessel, air separation unit) upstream the combined plant, modifying the structure of the combined plant itself which becomes an IGCC (Integrated Gasification Combined Cycle) plant. The aim of this case study is to compare the results obtained by the proposed analytical procedure of evaluation of *CET* when applied to similar plants burning two fossil fuels with different costs and CO_2 production (natural gas and coal). In this sense, as far as the coal utilization as fuel in a combined plant is concerned, it has been chosen to burn coal in a PFBC in order to modify the less is possible the structure of the combined cycle plant.

It has been decided to abate the NO_x under the law limits using an SCR, and the related costs are considered in the environomic optimization of the plant. Concerning the SO_x, it is negligible for the natural gas fired configuration, and it is reduced in the PFBC in the coal fired configuration.

a) CC burning natural gas

This represents the original configuration of the combined cycle plant (712 MW) (Arena et al., 1997). The power station is constituted by two separated and identical modules, that utilise the thermal coupling of two thermodynamic cycles. Each module is constituted by two gas turbines FIAT TG50D5, whose exhaust gas transfers their heat to two Heat Recovery Steam Generators (HRSG). The fuel is natural gas (LHV = 46795 [kJ/kg]). The steam is produced in the HRSG at two pressure levels. For each module there is one steam turbine, where the steam, coming from the two HRSG per module, expands. After the expansion, the steam is sent to the condenser (one for each module), and finally it is split in two parts and returns to the two HRSG. The condensers are cooled by two natural-draft cooling towers. A simplified Physical Model (PM) (*Figure 1*) of the plant has been adopted (Santarelli, 1998). First of all, just one module of the power station has been considered; therefore its power is 356 MW, 123 MW for each of the two gas turbine and 110 MW for the steam turbine. The SCR abatement unit for NO_x is also shown. The fuel used is natural gas, with a cost of c_f=4.5 10^{-6} \$/kJ.



1) Air Compressor
2) Combustion Chamber
3) Gas Turbine
4)Superheater HP
5) Evaporator HP
6) Superheater LP
7) Economiser HP
8) Evaporator LP
9) Economiser LP
10) Extraction Pump
11) Pump HP
12) Steam Turbine HP
13) Steam Turbine LP
14) Condensing and condensing supply works
15) Mixer

Figure 1. Combined Cycle Plant

b) CC burning coal

In this configuration, the plant is modified in order to burn the coal in a PFBC. The original gas turbine is modified, and the PFBC takes the place of the original natural gas combustor of the gas turbine: the resulting scheme is an air-cooled PFBC. This represents the only modification of the original plant, that remains the same for the HRSG and Steam Cycle sections.

The PFBC consists essentially of a refractory-brick lined cylinder containing sand-sized refractory particles kept in suspension by an upward flow of air bled from the compressor. The oxides of sulphur formed are trapped in the ash. *Figure 2* shows the scheme of the PFBC in conjunction with the gas turbine (Cohen et al., 1996; Comitato Termotecnico Italiano, 1993). It make use of the fact that heat is transferred between the fluidised bed and the solid surface immersed in it with very high heat transfer coefficients. In the adopted scheme, most of the compressor air is heated in the tubular heat exchanger in the bed, and only the small amount of air bled for fluidisation need be cleaned of dust in a cyclone separator before being passed to the turbine (Cohen et al., 1996; Comitato Termotecnico Italiano, 1993).

The pressure drop of the air flow is clearly higher in this configuration than with the natural gas combustor, and this is considered in the plant analysis. Coal is burned in the presence of sorbent at temperatures around 1125 K: above 1200 K there is the risk of a syntherisation of the fluidised bed; below 1025 K the combustion efficiency is too low; but the important factor deciding the temperature of the bed is the need of an *in situ* desulphuration, which operates well in a temperature near 1125 K (Comitato Termotecnico Italiano, 1993).

Of course, it is well known that the fluidised bed configuration has an investment cost considerably higher than the cost of a gas combustor; in fact, the configuration considered in the paper is not currently used. But, as previously said, here the aim is to compare the results obtained by the proposed procedure of evaluation of *CET* when applied to similar plants burning two fossil fuels with different costs and CO_2 production (natural gas and coal), and it has been therefore considered a pressurised fluidised bed combustor in order to modify the less is possible the structure of the combined cycle plant.

The fuel used is coal, with a cost of c_f =4 10^{-6} \$/kJ. To apply the proposed methodology of evaluation of the *CET*, it has to be determined the operation point of the plant, for natural gas and coal fired configurations. In each configuration, it is determined an optimal operation point using the proposed environomic objective function (15): this operation point represents the project point of the plant; the *UECs* used to calculate the *Efficiency Penalty* terms (3) and (5) are determined with a Thermoeconomic Analysis of the plant in the optimised operation point; the *Index of CO_2 Emission* is determined with (8), with (11) the amount of the annual environmental charge to be paid by the system, and finally with (12) it is determined the resulting cost per unit of CO_2 emitted.

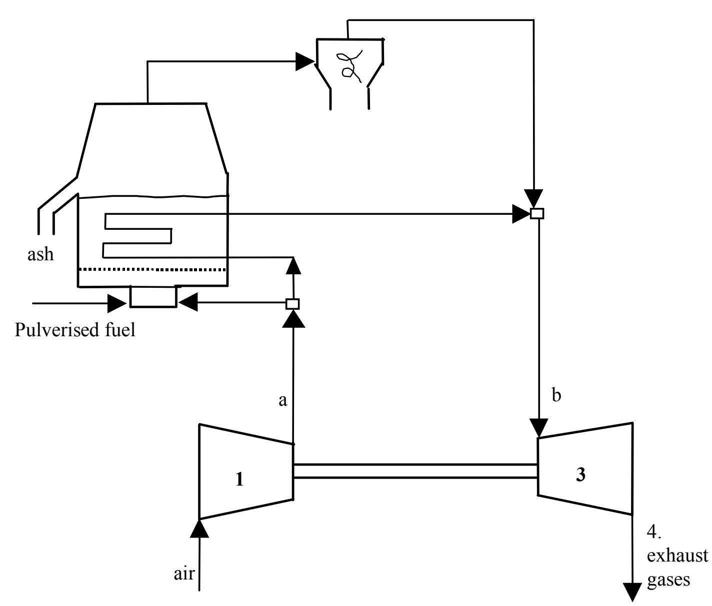


Figure 2. Pressurised fluidised bed combustor integrated with the gas turbine

The charge automatically varies if the plant efficiency, and thus its environmental performance, varies; the charge could be evaluated in some characteristic operation points (linked to the plant annual scheduled load), or even by means of a continuous monitoring of the plant efficiency (considering therefore also the part load operations); this represents just a methodological choice of data measurement (and thus could be a political decision), the procedure remaining the same.

To begin with the following operating conditions have been assumed: annual number of operation hours N=6000 h/yr, annual *CRF* of the components 10%, and maintenance factor ϕ=1.06; fuel cost c_f=4*10^{-6} \$/kJ for the coal, and c_f=4.5*10^{-6} \$/kJ for the natural gas. The plant efficiency (evaluated as the ratio of the electric power produced and the energy introduced with the fuel) for the two configurations is presented in TABLE I, with the *Index of* CO_2 *Emission* and the amount of the *Efficiency Penalty*. Of course, the natural gas fired configuration has the better efficiency: the coal fired configuration suffers of low temperature and high pressure drop in the combustor. Moreover the natural gas fired configuration has the lower value of the *Index of* CO_2 *Emission* because it burns natural gas. The *Efficiency Penalty* is lower for this configuration, even if the unit cost of the natural gas is higher than that of coal, because the higher efficiency of the natural gas fired plant reduces the effect of the high cost of natural gas in the determination of the *Efficiency Penalty* amount.

In TABLE I are illustrated also the values of C_{CO2} per unit of CO_2 emitted (*CET*), calculated in two ways: considering just the cost of destroyed exergy (3), or considering both the cost of destroyed exergy (3) and residual exergy (5) in the objective function (15). The highest *CET* is the one of the coal fired configuration: in fact, this is due to the higher value of the *Efficiency Penalty* (due to the lower efficiency of the coal fired configuration), and above all to the role of the I^*_{CO2}, which is higher for the coal fired configuration because of the higher CO_2 emissions of coal and the lower efficiency of the plant. The obtained results show that the proposed procedure of evaluation of a charge on the CO_2 emissions awards the better efficiency and environmental performance of a plant.

In TABLE I is illustrated also the influence of the *CET* previously evaluated on the cost of the electricity produced by the plant; in the graph is shown the absolute increase of electricity cost due to the imposition of *CET* ($c_{el,CET}$, equation 13), and also the percentage increase of the electricity cost respect its original cost without the imposition of *CET* ($\Delta c_{el,CET}$, equation 14): The two plant configurations are evaluated at the same W_{el} and N, and thus at the same energy production. The Coal Fired configuration has the highest *CET* value, and therefore it has also the highest $c_{el,CET}$ and $\Delta c_{el,CET}$. This result is due to the lower efficiency of the Coal Fired configuration, which uses badly scarce energy resources: it has the highest value of *CET* and at the same time the highest emission of ton of CO_2, and this explain the high impact of the *CET* on the kWh of electricity produced.

TABLE I. VALUES OF EFFICIENCIES, I^*_{CO2}, Π_ε, CET AND ITS EFFECT ON THE ELECTRICITY COSTS IN THE CASE OF THE TWO PLANT CONFIGURATIONS

Parameter	Natural gas fired configuration	Coal fired configuration
Plant efficiencies	0.479	0.432
I^*_{CO2}	0.44	0.833
Π_ε **(M\$/yr)**	41.616	48.407
CET **(\$/ton$_{CO2}$)**	Eq. (4) $\rightarrow$ 18.59 Eq. (4)+(6) $\rightarrow$ 19.48	Eq. (4) $\rightarrow$ 20.34 Eq. (4)+(6) $\rightarrow$ 22.26
Increase of electricity cost due to *CET* (c\$/kWh)	0.86 ($\Delta c_{el,CET}$ = 21.7 %)	1.89 ($\Delta c_{el,CET}$ = 40.9 %)

To develop a deeper analysis of the results obtained by the proposed methodology applied on the two combined plant configurations, it is also possible to evaluate the results obtained in different operating conditions, that is varying the annual number of operation hours *N* and the fuel cost c_f for the coal and for the natural gas. In this way it will be investigated the results obtained for different economic scenarios, linked with the fuels costs. Concerning the parameter *N*, it has been considered two values: *N*=6000 (h/yr) and *N*=8000 (h/yr); the fuels costs are varied around their present values, utilized in the base case conditions. For each plant configuration, in each different situation the methodology is repeated (Thermoeconomic Analysis, optimization using (15), determination of the Π_ε amount (7), determination of I^*_{CO2} (8), and finally determination of cost per unit of CO_2 emitted *CET* (12)).

The results obtained for the Π_ε are shown in *Figure 3* for the natural gas fired configuration, and in *Figure 4* for the coal fired configuration.

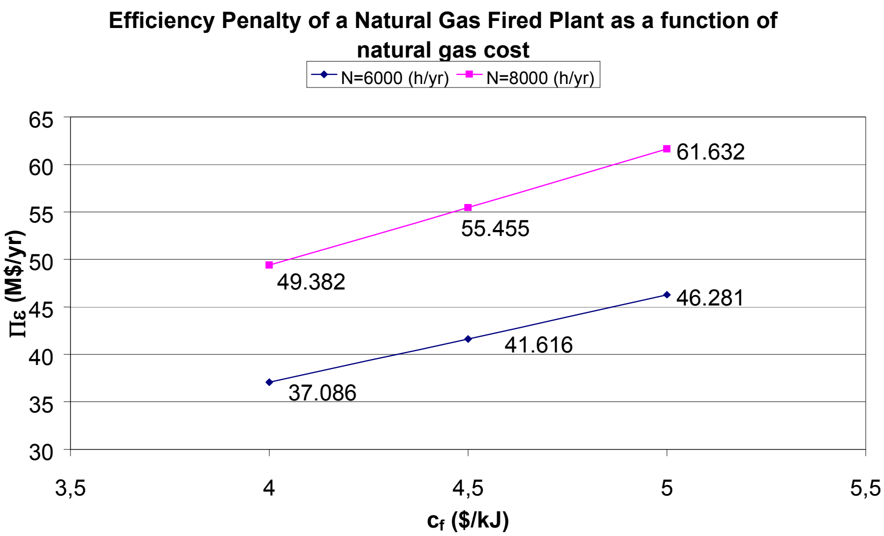


Figure 3. Efficiency Penalty of natural gas fired configuration

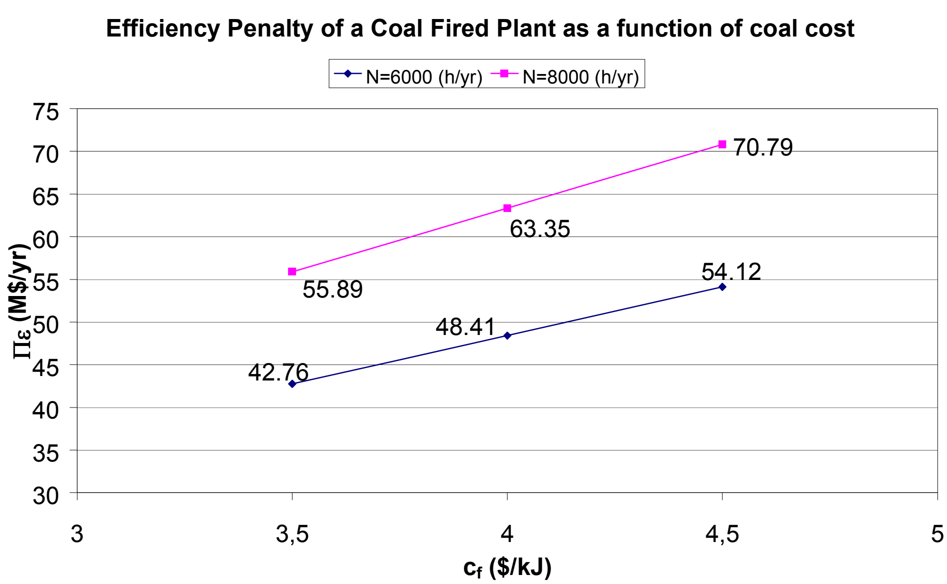


Figure 4. Efficiency Penalty of coal fired configuration

The Π_ε values increase with N and c_f. It is interesting to see the results obtained by the two plant configurations for the same values of N and c_f: considering c_f=4.5·10^{-6} \$/kJ, the coal fired plant suffer an higher amount of Π_ε than the natural gas fired plant, and this is due to the lower efficiency of the plant operation; so with the same value of c_f the coal fired configuration is more penalised.

The results obtained for the *CET* are shown in *Figure 5* for the natural gas fired configuration, and in *Figure 6* for the coal fired configuration.

The values are not significantly affected by the annual number of operating hours *N*. The *CET* values are a little lower for *N*=8000 (h/yr), because the operation point is determined via an optimization using (15). For higher *N* the weight of the destroyed and residual exergy (expressions (4) and (5)) in the objective function raises, and therefore the optimization procedure promote the reduction of the irreversibility in the unit time and consequently the *CET* is lower than for the case *N*=6000 (h/yr).

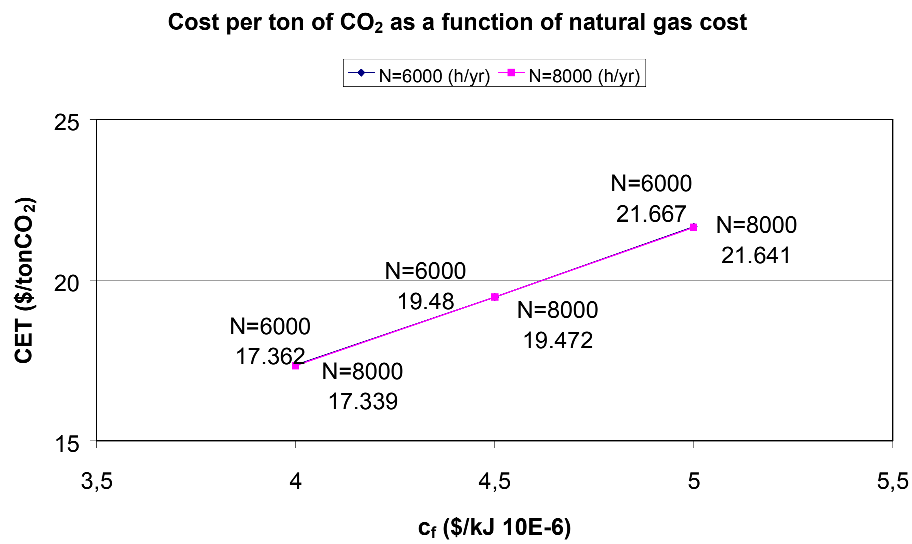


Figure 5. CET for natural gas fired configuration

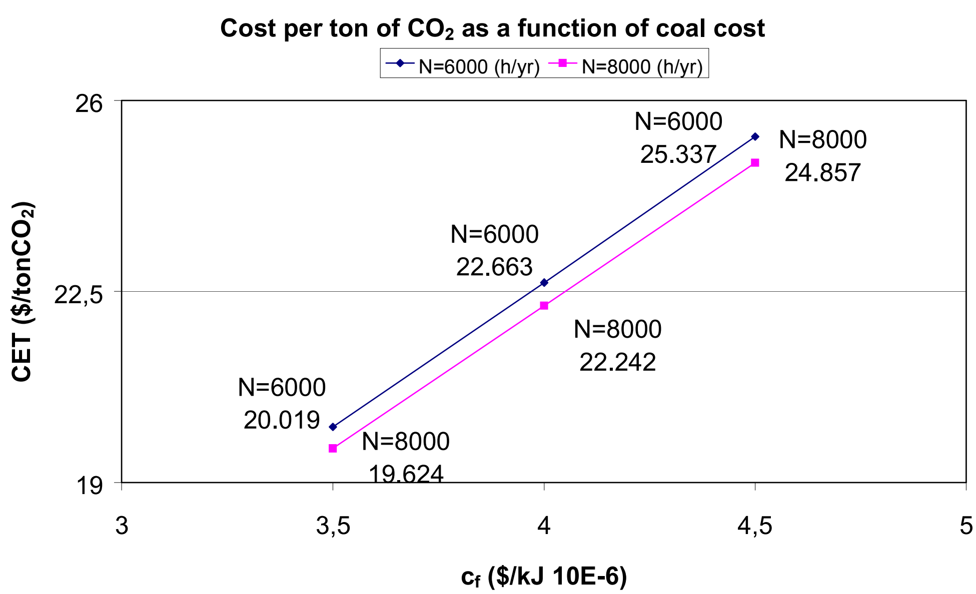


Figure 6. CET for coal fired configuration

As discussed in the previous section, the values are affected by the fuel cost: in the methodology, the cost of the destroyed and residual exergy is proportional to the fuel cost, because the destruction and loss of exergy is equal to the destruction of valuable primary fuel. The methodology therefore links the *CET* to the fuel cost: if the fuel cost increases, then does the *CET*. Also for the *CET* it is interesting to see the results obtained by the two plant configurations for the same values of *N* and c_f: considering c_f=4.5·10^{-6} \$/kJ, the coal fired plant suffer an higher amount of Π_ε than the natural gas fired plant, and this is due to the lower efficiency of the plant operation, and to the higher value of the I^*_{CO2}; so with the same value of c_f the coal fired configuration is more penalised.

In *Figure 7* and *Figure 8* is illustrated the influence of the *CET* on the cost of the electricity produced by the plant obtained varying the annual number of operation hours *N* and the fuel cost c_f for the coal and for the natural gas; in the graph it is shown the absolute increase of electricity cost due to the imposition of *CET* ($c_{el,CET}$), and also the percentage increase of the electricity cost respect its original cost without the imposition of *CET* ($\Delta c_{el,CET}$):

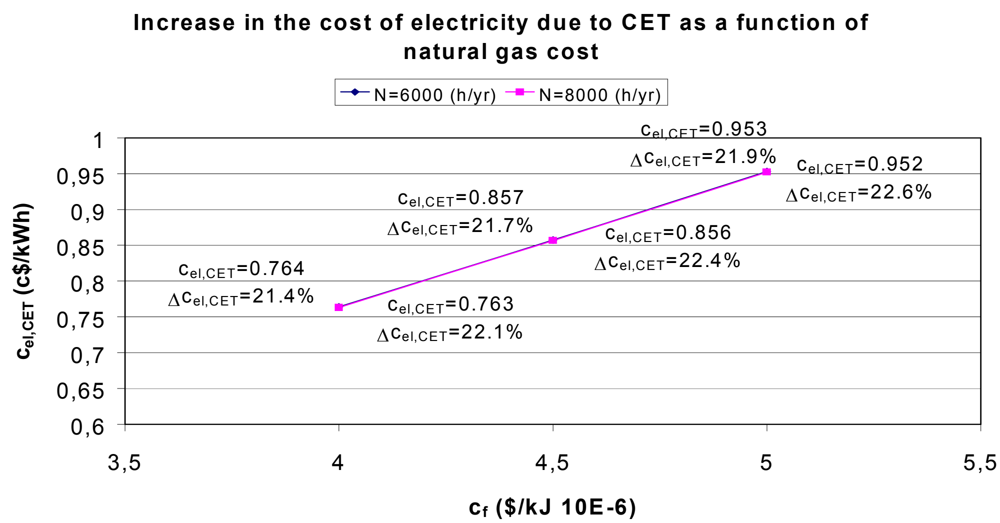


Figure 7. Absolute and percentage increase in the cost of electricity due to CET as a function of natural gas cost

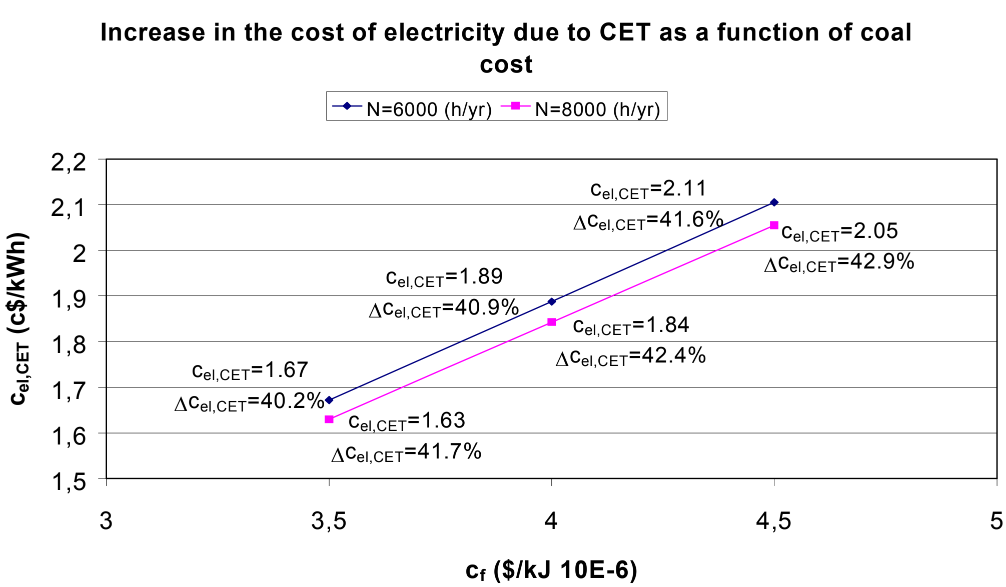


Figure 8. Absolute and percentage increase in the cost of electricity due to CET as a function of coal cost

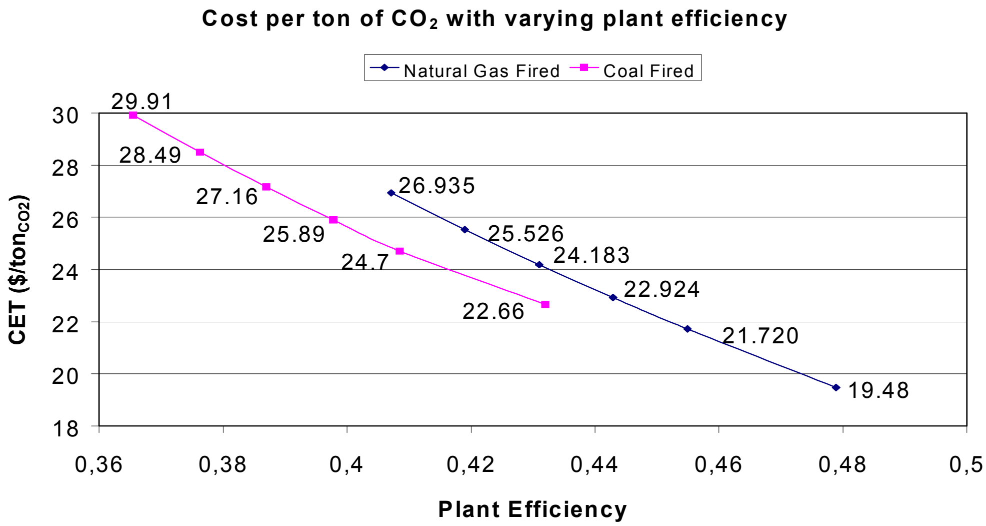


Figure 9. CET with varying the efficiency of the two configuration

For these results are valid the same comments developed for the values of *CET* presented in *Figures 5* and *6*, concerning the dependence of the results on the values of *N* and c_f. The values of $c_{el,CET}$ and $\Delta c_{el,CET}$ have the same behaviour of the *CET*.

Finally, it is possible to investigate the values of the *CET* in case of variations in the plant efficiency. In this situation it is evaluated the Π_ε, the I^*_{CO2}, the C_{CO2} and finally the *CET*. This is done for various reductions of the plant efficiency, and for each power plant. The results obtained are shown in *Figure 9*.

As it is shown, in case of reduction of plant efficiency the *CET* increases. This is expected, because in case of reduction of efficiency the pollutant emissions increase., and the plant is punished for the efficiency reduction. For both the plant configurations, in case of a reduction of efficiency in the order of 15%, the cost increases in the order of 38%. With the same plant efficiency, the natural gas fired plant has an higher value of *CET*, because of the higher cost of natural gas (determining an higher value of Π_ε), but the difference is not too high due to the role of the I^*_{CO2}, that is lower for the natural gas fired configuration. The Natural Gas is more penalised because it is a more valuable fuel than coal, and therefore its inefficient utilization has to be discouraged.

The same evaluation can be done to investigate the values of $c_{el,CET}$ and $\Delta c_{el,CET}$ in case of variations in the plant efficiency; the results are shown in *Figure 10* for both plant configurations:

The behaviour of $c_{el,CET}$ and $\Delta c_{el,CET}$ is obviously strictly linked with the one of *CET*: for both the plant configurations, in case of a reduction of efficiency in the order of 15%, the cost increases in the order of 60%. With the same plant efficiency, the Natural Gas Fired configuration has still lower values of $c_{el,CET}$ and $\Delta c_{el,CET}$: it pays an higher value of *CET* (see *Figure 9*) but it emits a widely lower mass of CO_2 than the Coal Fired configuration; the values of C_{CO2} are lower for the Natural Gas Fired configuration because of the role of the I^*_{CO2}, (which is lower for the Natural Gas Fired configuration: the relation is in the order: $I^*_{CO2,\ natural\ gas} = 0.5\ I^*_{CO2,\ coal}$, see TABLE I).

5. Comparison of the Obtained *CET* Values with the Break-even Values of CT vs. CO_2 Sequestration Costs

In a previous paper (Santarelli et al., 1999b) it has been determined the break-even values of the Carbon Tax face to different values of the costs of the CO_2 sequestration activities c_{seqCO2} expressed in \$/tonCO_2: for each value of the c_{seqCO2} it has been calculated the value of CT limit, over which it is convenient to sequestrate the CO_2 and under which it is convenient to emit the CO_2 and to pay the relative CT. This has been done considering that the sequestration activity causes a reduction of the plant efficiency, in the two extreme cases of plant efficiency reduction of 3% and 10%.

The results obtained for the break-even values of CT vs. the CO_2 sequestration costs are summarised in *Figure 11*, this figure refers to the natural gas fired combined cycle plant of *Figure 1*.

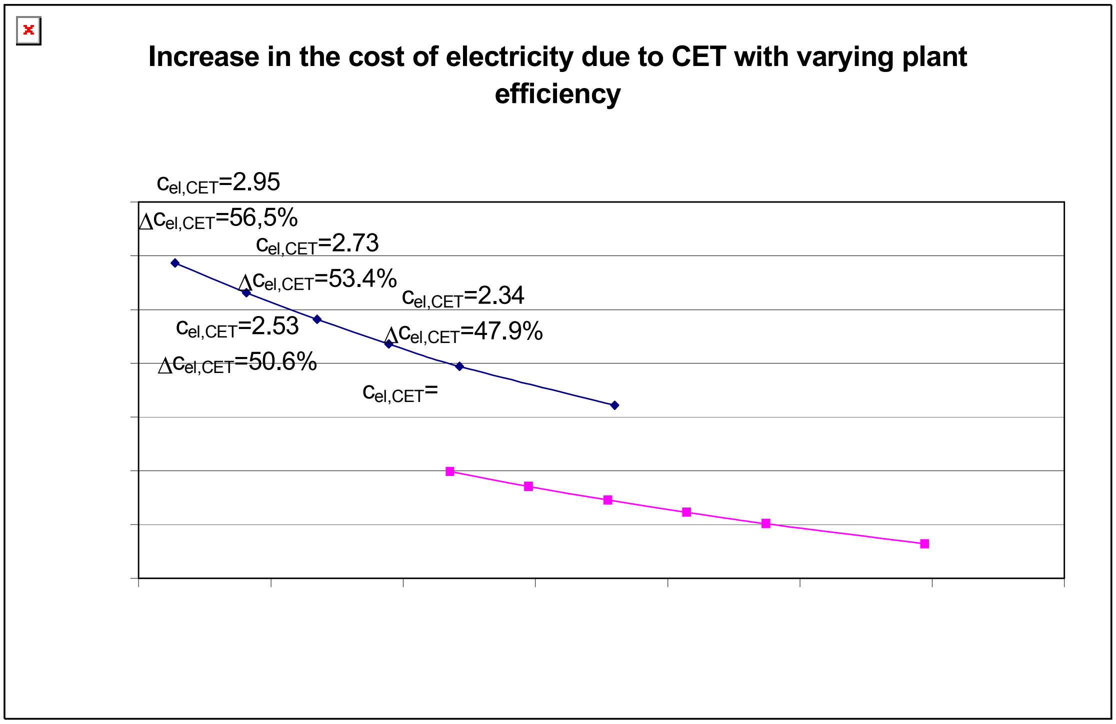


Figure 10. Absolute and percentage increase in the cost of electricity due to CET with varying the plant efficiency in the two configurations

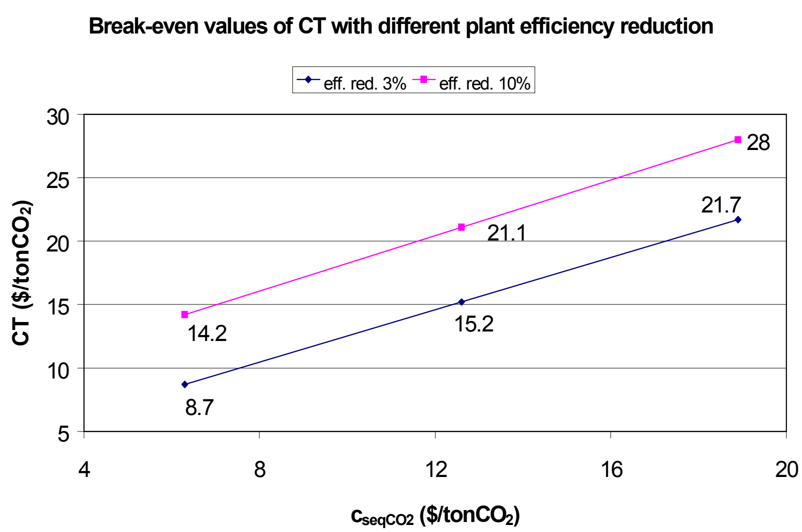


Figure 11. Break-even values of CT *of the natural gas fired configuration*

Considering the values of the *CET* calculated with the proposed methodology (TABLE I and *Figure 5*), it is evident that these values are similar to the break-even values of CT shown in *Figure 11*. So it is shown that the proposed analytical procedure of the charge on the unit ton of emitted CO_2 gives results that are close to the CT break-even values, as already discussed in (Borchiellini et al., 2000).

6. Conclusions

Considering the results obtained, the following points can be underlined:

i. environomics allows detailed information on power plant design including pollutant emissions and abatement or sequestration influences to be evaluated;
ii. in order to determine a proposition of environmental charges of power plant, it is possible to use the concepts of *Efficiency*

Penalty and *Index of CO_2 Emission.* The charge is obtained not on the basis of political considerations, but the proposed approach is linked just to the thermodynamics and efficiency of the energy system. The charge automatically varies if the plant efficiency, and thus its environmental performance, varies; the charge could be evaluated in some characteristic operation points (linked to the plant annual scheduled load) or even by means of a continuous monitoring of the plant efficiency;

iii. developing the expression used for the evaluation of the *CET*, it is possible to show the connections between the *CET* and some thermoeconomic concepts (Unit Exergetic Cost, Productivity Lack and Residual Exergy Loss);

iv. the approach allows the cost per unit ton of CO_2 emitted to be evaluated: the values obtained are close to the Carbon Tax break-even values;

v. the environmental charges, and thus the cost per unit ton of CO_2 emitted, are not absolute, but they depend on the plant considered and its fuel. In this paper the influence of the fuel burned in similar plants on the cost per unit of CO_2, determined by the proposed analytical methodology, has been investigated.

Acknowledgements

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Appendix

The *Index of CO_2 Emission* (expression 9) could also be expressed as:

$$I^*_{CO_2} = \frac{1}{I_{CO_2 rif}} \cdot \frac{3.67 \cdot [C] \cdot G_f}{[\Psi_f - (\Psi_{irr} + \Psi_w)]} = = \frac{1}{I_{CO_2 rif}} \cdot \frac{3.67 \cdot [C] \cdot G_f}{LHV \cdot G_f - \left[\sum_{i=1}^{N_{components}} (\Psi_e - \Psi_o)_i + \sum_{r=1}^{N_{wastes}} \Psi_w \right]} \quad (A.1)$$

As an example, the term $3.67 \cdot [C]$ assumes the value 2.75 for natural gas and 3.1 for coal. Equation (9) shows the relation among I^*_{CO2}, the CO_2 emissions and the inefficient utilization of the energy resources ($\Psi_{irr} + \Psi_w$).

The charge imposed to the CO_2 emitted by the plant C_{CO2} (expression 10) could be developed as:

$$C_{CO_2} = \frac{1}{I_{CO_2 rif}} \cdot \frac{3.67 \cdot [C] \cdot G_f}{[\Psi_f - (\Psi_{irr} + \Psi_w)]} \cdot 3600 N [C_{irr} + C_w] \quad (A.2)$$

that is

$$C_{CO_2} = \frac{1}{I_{CO_2 rif}} \cdot \frac{3.67 \cdot [C] \cdot G_f}{LHV \cdot G_f - \left[\sum_{i=1}^{N_{components}} [\Psi_e - \Psi_o]_i + \sum_{r=1}^{N_{wastes}} \Psi_w \right]} \cdot 3600 N \left[\sum_{i=1}^{N_{components}} c_{e_i} [\Psi_e - \Psi_o]_i + \sum_{r=1}^{N_{wastes}} c_w \Psi_w \right] \quad (A.3)$$

It can also be developed in this expression:

$$C_{CO_2} = \frac{1}{I_{CO_2 rif}} \cdot \frac{3.67 \cdot [C] \cdot G_f}{\Psi_p} \cdot 3600 N \cdot \left[\sum_{i=1}^{N_{components}} c_{e_i} [\Psi_e - \Psi_o]_i + \sum_{r=1}^{N_{wastes}} c_w \Psi_w \right] \quad (A.4)$$

$$C_{CO_2} = \frac{1}{I_{CO_2 rif}} \cdot 3.67 \cdot [C] \cdot G_f \cdot 3600 \cdot N \cdot \left[\frac{\sum_{i=1}^{N_{components}} c_{e_i} [\Psi_e - \Psi_o]_i}{\Psi_p} + \frac{\sum_{w=1}^{N_{wastes}} c_w \Psi_w}{\Psi_p} \right] \quad (A.5)$$

where

$$\frac{[\Psi_e - \Psi_o]_i}{\Psi_p} = \xi_i \quad (A.6)$$

is the ratio between the irreversibility of the *i* component and the exergy product of the plant; it is defined *Productivity Lack* ξ_i in (Santarelli, 1998; Arena et al., 1997); the term

$$\frac{\Psi_w}{\Psi_p} = \xi_w \quad (A.7)$$

could be defined in the same way as *Residual Exergy Loss* ξ_w.

It could therefore be seen that the C_{CO2} is linked to the ξ_i of each component of the plant. The cost per unit ton of CO_2 emitted (expression 12) could be expressed as:

$$CET = I^*_{CO_2} \cdot \frac{\Pi_\varepsilon}{G_{CO_2}} = \frac{1}{I_{CO_2 rif}} \cdot \frac{G_{CO_2}}{\Psi_p} \cdot \frac{\Pi_\varepsilon}{G_{CO_2}} \quad (A.8)$$

that is

$$CET = \frac{1}{I_{CO_2rif}} \cdot 3600N \cdot \left[\frac{\sum_{i=1}^{N_{components}} c_{e_i} [\Psi_e - \Psi_o]_i}{\Psi_p} + \frac{\sum_{w=1}^{N_{wastes}} c_w \Psi_w}{\Psi_p} \right] \tag{A.9}$$

and finally

$$CET = \frac{1}{I_{CO_2rif}} \cdot 3600N \cdot \left[\sum_{i=1}^{N_{components}} c_{e_i} \xi_i + \sum_{w=1}^{N_{wastes}} c_w \xi_w \right] \tag{A.10}$$

showing the links between the proposed *CET* and the ξ_i and ξ_w.

Nomenclature

$[C]$	carbon mass percentage in the fuel
C_{CO2}	economic charge imposed to the total CO_2 emissions [$/y]
c_{coal}	economic cost of coal [$/kg$_{coal}$]
c_f	unit economic fuel cost [$/kJ]
c_e	unit efficiency penalty of input exergy flow [$/kJ]
c_w	unit efficiency penalty of residual exergy flow [$/kJ]
c_{el}	electricity production cost before the imposition of *CET* [c$/kWh]
$c_{el,CET}$	absolute increase of electricity cost due to the imposition of *CET* [c$/kWh]
c_{seqCO2}	economic cost of CO_2 sequestration activities per ton of CO_2 [$/ton$_{CO2}$]
C_f	annual cost of the fuel consumption [$/yr]
C_p	annual cost of environmental pollution [$/yr]
C_r	annual cost of resources utilized by pollution abatement units [$/yr]
C_{irr}	cost of destroyed exergy [$/s]
C_w	cost of residual exergy [$/s]
CRF	Annual Capital Recovery Factor
CET	Carbon Exergy Tax [$/ton$_{CO2}$]
CT	Carbon Tax [$/ton$_{CO2}$]
F	objective function
G_{CO2}	mass flow of CO_2 emitted by the plant in one year [kg/yr]
G_f	fuel mass flow rate [kg/s]
I^*_{CO2}	*Index of* CO_2 *Emission* [kg$_{CO2}$/kWh]
I_{CO2rif}	*Reference Index of* CO_2 *Emission* [1 kg$_{CO2}$/kWh]
LHV	Low Heating Value of system fuel [kJ/kg]
N	number of hours of plant operation per year [h/yr]
UEC	Unit Exergetic Cost [kJ/kJ]
W_{el}	plant electric power output [MW]
x	decision variables vector
Z_I	annual recovered investment cost of the components of the plant [$/yr]
Z_A	annual recovered investment cost of the pollution abatement units of the plant [$/yr]

Greek letters

$\Delta c_{el,CET}$	percentage increase of the electricity cost compared to its original cost without the imposition of *CET*
Π_ε	Efficiency Penalty [$/yr]
ϕ	maintenance factor
ξ_I	Productivity Lack [kJ/kJ]
ξ_w	Residual Exergy Loss [kJ/kJ]
Ψ	exergy flow [kW]
Ψ^*	exergetic cost of an exergy flow [kW]
Ψ_f	fuel exergy [kW]
Ψ_{irr}	exergy destroyed by irreversibility in the plant components [kW]
Ψ_p	Exergy flow of the product of the energy system [kW]
Ψ_w	residual exergy rejected by the plant [kW]
Ψ_e	input exergy flow [kW]
Ψ_o	output exergy flow [kW]

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