Ecological payback in national energy matrix: analysis of wind energy expansion

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Summary: Sustainable development concern has become subject of recurrent discussions over the last years due to the duet large greenhouse gases emissions and world growth, especially in developing countries. Electrical sector is one of the major segments responsible for greenhouse gases emissions, but also the one in which modern society depends the most for life standard maintenance, economic and social activities. A renewable source considered in Brazilian energy sector expansion is wind power, which has a 143 GW potential. As such, the paper aims to estimate environmental impacts (CO_2 emission) involved in wind power plants construction phase and return time for compensating these emissions during operation. Ecological payback is developed through CO_2 emission analysis of different energy sectors required as inputs in construction and final emission reduction due to this "clean" power plant operation in national electrical matrix. Estimation of economic and environmental impacts is based on input-output methodology, using a 2004 matrix for Brazilian economy. Results point out for a maximum payback period of 4 months in worst case scenario, and major pollution contribution of Steel and Products Manufacturing during construction.

1. Introduction

Brazilian energy matrix is mainly dependent on renewable energy sources which accounted for 45.9% of internal energy offer (IEO) in 2007, highlighting sugar-cane products (15.9%) and hydropower and electricity (14.9%) (MME, 2008). In relation to electricity generation in 2007 total production reached 44.6 TWh, 6.0% superior to 2006. Hydropower plants were responsible for 85.5% of total electricity generation in 2007 (Graph 1), followed by biomass (4.1%) and natural gas (3.3%). Wind power is still underutilized, accounting for just 0.1% of electricity or 559 GWh in 2007 (ONS, 2008).

Brazilian energy structure is one of the lowest pollutant in comparison with other countries with a tCO_2/(toe of IEO) coefficient of 1.57 compared to United States (2.49), Latin America (1.88) and world (2.37) (MME, 2008). Nevertheless, high concentration on hydro plants in relation to all energy sources and between renewable sources leads to important energy security issues. In order to mitigate these risks, electricity infrastructure relies in a group of transmission lines, stations and power plants interconnected in a dense network that reaches 96.6% of all electricity generation capacity of the country. The “Sistema Integrado Nacional” (SIN) connects power plants to load centers and is under the “Operador Nacional do Sistema” (ONS) responsibility, which activate/disable plants to supply variable electricity demand and bypass energy restrictions. According to ONS, electric energy charge in SIN for 2006 was 415.8 TWh, 92% supplied by hydropower plants, 5% thermal plants and 3% nuclear plants (BM&F, 2008).

Electricity demand forecast estimates 5.1% annual expansion rate until 2015, which will require large investments in energy generation (EPE, 2006b). Although the historical evolution of generation capacity over time has not followed internal energy requirements (Análise, 2008), the government Growth Acceleration Program (PAC) plans to raise IEO by 12,386 MW, focusing on conclusion and expansion of nuclear power plants. The program brings discussions about energy matrix diversification when future hydro plants projects reveal more environmental impact as they move to Amazon region. In a sustainability development scenario, new alternative energies as solar and wind power become options to extend energy matrix. Although still financially expensive, internalization of ecological costs in traditional plants makes them very competitive.

A growing awareness that environmental impacts caused by countries development can restrict its own progress with costly impacts on future generations (Inatomi; Udaeta, 2005) has led to a more rational use of available resources. Several efforts in sustainable development issues have begun with Rio 92 Conference, followed by Kyoto Protocol and IPCC (Intergovernmental Panel for Climate Change). Around 35% of greenhouse effects gases emissions come from energy use, which considers electricity generation sector (Table 1).

Consequently the analysis of socio-environmental characteristics of new generation investments becomes essential to a more efficient evaluation of available alternatives which will affect society in short and long terms. This paper seeks to contribute to this analysis, evaluating required operation time of wind plants to compensate pollution from their construction.

2. Wind Power Plants Overview

Use of wind power for electricity purposes became relevant in the 1970's due to two oil embargos in the decade and a consequent search for new energy sources to reduce energy security risks. Research centers were developed to make wind power economic viable and more efficient to implementation in several countries (Tolmasquim, 2005). Nowadays wind power is one of the cheapest renewable sources available considering turbine cost by nominal power, due to technical advances in last 15 years (Tolmasquim, 2005).

The Nuclear Energy Agency (NEA) has developed a comparative study of costs within different plants types in 2005 with 63 countries. Overnight costs, operation and maintenance (O&M) expenses and fuel prices were estimated for power plants life. For comparative reasons, only onshore wind plants were selected and data for Brazil taken from Tolmasquim (2005). As noticed, Brazilian costs are compatible with international average due to, especially, a national factory for wind turbines (Graph 2).

However, in Brazilian case due to high hydro and crops potential available, wind power plants are not still very competitive when compared to other energy sources (Graph 3). In order to change this scenario it was developed the Alternatives Sources Incentive Program (PROINFA) which aims to integrate renewable sources parks into NIS in the short term, offering financing to investors (ANEEL, 2005).

According to ANEEL (2008), there are 18 wind farms in operation (autoproduction and integrated to NIS) totalizing 289,150 MW installed and 21 projects in construction that will add 446,830 MW to the energy matrix.

Wind power plants do not release greenhouse gases during operation, but have some environmental issues related to noise, electromagnetic interference, visual pollution and fauna (Inatomi; Udaeta, 2005). Noise is produced mechanically (gearbox) and aerodynamically (blades motion) although developments in recent years has result in new turbines technologies less noisy during air current variations (European

Commission, 1995). Another potential burden is electromagnetic interference due to interaction of the blades with communication signals. Visual impacts come from stroboscopic effect, which can be caused by sunlight “flicker” when passing through the blades and visual annoyance by the structure itself (European Commission, 1995). Data from bird accidents reveal low impacts when towers are placed out of migration routes (Inatomi; Udaeta, 2005).

Significant advantages of large wind farms integrated to NIS besides pollution reduction are lower necessity of reservoir construction for hydro plants and mitigate energy security risks during dry seasonal periods (ANEEL, 2005). This complementary characteristic is especially important in Northeast region where dry periods have strong air currents in the coast.

In relation to economic impacts, they can be identified in two stages: construction, which produces a short term demand; and O&M, which has long term effects on the economy (NWCC, 2003). Several international studies have been done using specific Input-Output (I-O) models such as IMPLAN, JEDI and RIM for wind farms impacts. Nevertheless, direct comparison is not possible once regional economic structure differs between locations and results are applied only in specific sites. Some studies are shown in Table 2.

Jobs per MW coefficients range from 0.36 to 16.2, depending on equipment availability and construction site relief. Total income during construction varies according to total jobs created and financial leaks. In general, large economic dynamic occurs during construction phase and income improvement and tax reduction during operation (NWCC, 2003). However, wind projects especially in countryside locations have several leaks due to large economic dependency on other regions. This reflects in large temporary work migration and income benefits outside the county (NWCC, 2003).

3. Methodology

3.1 Literature Review

Current discussions on sustainable development have induced the emergence of several methodologies in an attempt to merge environmental aspects into economic evaluation, generally considering monetization of externalities in decision functions for new investments. However, the main issue in externalities evaluation caused by pollution relies on the difficulty to convert environmental impacts into monetary values once there are not externalities markets.

ExternE project (European Commission, 2005) has become a reference proposing the quantification and valorization of electricity sector emissions impacts on public health through Impact Pathway Approach Methodology (IPA). Monetary costs account is done based on pollutant concentration and dose-response functions for a certain region. Nevertheless, it does not consider the impacts over flora and fauna.

According to the concept of Life Cycle Analysis (LCA), defined by Perriman (1993) as: “a process for evaluating the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wasted discharged to the environment, assessing the impact on the environment of those energy and material uses and waste releases, and identifying ways for reducing the environmental impacts.”, externalities evaluation should include different economic-environmental relations both direct and indirect impacts (Carvalho, 2000).

Following this wider concept, another approach is developed by I-O models (which accounts for interindustrial relations in an economy) adapted to environmental issues. According to Hilgemberg (2004) these models allow better visualization of pollution intensity and opportunity-cost from resources use in relation to carbon emissions.

From this methodology, three environmental I-O models categories can be identified (Miller; Blair, 1985): Economic-Ecological Models, Commodity-by-Industry Models and Generalized Input-Output Models.

Economic-Ecologic Models, also known as fully integrated models (Miller; Blair, 1985), include ecosystem sectors and flows between economic and environmental spheres through interregional relations. An ecosystem submatrix is added to the interindustry framework allowing transactions with the economic side. The first work in this area was developed by Cumberland, who used an industry-by-industry model to acquire economic interactions of proxy variables to environmental costs and benefits (Hilgemberg, 2004). After, Daly built a model based on human and not human sectors, analyzing economic, environmental and economic-environmental flows within them (Hilgemberg, 2004). Nevertheless, valuation of negative and positive externalities and data requirement are important issues that restrict the implementation of the models.

The problem of working with environmental and economic units, not comparable directly, is solved by Commodity-by-Industry Models which allow industries to produce commodities and waste products from industrial process (Hilgemberg, 2004). Isard's model relates economic and ecological activities through flows within industry and natural environment (specifically terrestrial and marine). Economic coefficients are endogenous to the model and ecological coefficients are exogenous. Consequently the latter is a limitation to the methodology application once requires large data volume (Miranda, 1980). Another critic is the linearity of environmental relations functions, unfeasible with reality (Miranda, 1980).

Victor's model includes lines in a commodity-industry matrix with ecological inputs and subproducts from industrial process, restricting Isard's model to focus only on flows of ecological products to economy and waste products from economy to environment (Miller; Blair, 1985). Its advantage is not use monetary values for environmental products and inputs. However, it considers just industry-environment impacts and not environment-industry impacts (Miranda, 1980).

In Generalized Input-Output Models, augmented Leontief model considers the relations within environmental impacts and the economic structure (Hilgemberg, 2004). Recently, several works have employed hybrid input-output models, in which interindustrial transactions of energy are measured in physical units and others transactions in monetary units (Miller; Blair, 1985). According to Miller and Blair (1985), such models account for the energy consumed in production of a good and the energy consumed in production of the inputs employed. It allows attaching emission coefficient vectors to study the environmental impact of all product life cycle. Examples can be found in Casler and Blair (1997), who studied emissions from fuel combustion in United States in 1985, and in Labandera and Labeaga (2002), who estimated carbon intensity in Spain in 1992 and analyzed the price impact of carbon taxes.

For this initial study, however, a more simple methodology has been developed, considering energy intensity issues in industry and associated pollution with electricity consumption. The methodology is described next.

3.2 Input-Output model

Input-Output models provide a wider vision of sectors interdependency through the analysis of products produced and consumed in a certain region. Such information are concentrated in an economy structure matrix (Z), in which the rows represent the production of a certain industry in all economy and the columns represent inputs required from different industries to accomplish its production.

In the economy, production of a good or service has two consumption destinies: directly consumed by final demand or used as input in the production of another good/service (intermediary consumption). Denoting by X_i sector *i* total production, z the intermediary consumption of its production by *n* sectors of the economy (including the consumption of the own industry) and Y_i final demand of sector *i*'s production, we have the following relation:

$$X_i = z_{i1} + z_{i2} + \cdots + z_{ii} + \cdots + z_{in} + Y_i \qquad (1)$$

It is important to state an intrinsic hypothesis to this I-O Model: interindustrial flows from *i* to *j*, for example, depends entirely on sector *j*'s total production in a determined time horizon. The technical coefficient (a_{ij}) is the relation between the share of sector *j*'s production used by sector *i* (z_{ij}) and sector *j*'s total production (X_j), and is supposed constant according to the premise of constant returns of scale (Miller; Blair, 1985).

$$a_{ij} = \frac{z_{ij}}{X_j} \qquad (2)$$

Fixed technical coefficients implies a methodology limitation once the own economy dynamics causes coefficient variations over time and consequently, analysis and inferences of the models are valid only to a short term horizon (Labandera and Labeaga, 2002).

Replacing (2) in (1) and rearranging, for *n* sectors:

$$(1-a_{11})X_1 - a_{12}X_2 - \cdots - a_{1i}X_i - \cdots - a_{1n}X_n = Y_1$$
$$-a_{21}X_1 + (1-a_{22})X_2 - \cdots - a_{2i}X_i - \cdots - a_{1n}X_n = Y_2$$
$$\vdots$$
$$-a_{i1}X_1 - a_{i2}X_2 - \cdots + (1-a_{ii})X_i - \cdots - a_{in}X_n = Y_i$$
$$\vdots$$
$$-a_{n1}X_1 - a_{n2}X_2 - \cdots - a_{ni}X_i - \cdots + (1-a_{nn})X_n = Y_n$$

In matrix form and solving the equations to determinate total output required to final demand (*Y*):

$$X = (I-A)^{-1}Y \tag{3}$$

$(I - A)^{-1}$ is Leontief Inverse matrix, which indicates all requirements for the economy's production, direct (from final demand) and indirect (from intermediary demand). It reflects how final demand propagates inside the entire economy (Miller; Blair, 1985).

In order to analyze impacts from construction and operation of a power plant in relation to its CO_2 emissions, it is defined an auxiliary vector for energy intensity (*e*) that determines electrical consumption required (MWh) to produce R$ 1 million of a certain sector *j*:

$$e_j = \frac{CTE_j}{X_j}$$

Obtained by:

$$e = \left(\hat{X}^{-1}\right)CTE$$

Where CTE is a nx1 vector with total electrical consumption in one year for each industry in the economy.

This definition, however, differs from engineer definition of energy intensity. Intensity, in engineer, is measured by total energy requirement divided by added value in the product; in this paper, energy intensity is measured by total energy requirement divided by total production value, not just added value.

Final necessary element is emission coefficient (tCO_2) for each MWh consumed in the economy, denoted "c". Taking the electricity consumption structure divided by source, it is possible to determine CO_2 emission rates for each power plant type and divide total pollution released during plant's operation for total electricity generation. Total CO_2 emission for a given year (P) is calculated by:

$$P_T = cX'e$$

Analysis is done in two steps: first, we calculate total production ($\dot{X}$), direct and indirect, resulted from power plant construction ($\dot{Y}$). Those values are converted in CO_2 emissions in order to determine total CO_2 released during implantation ($\dot{P}_{construction}$).

$$\dot{X} = (I - A)^{-1}\dot{Y}$$

$$\dot{P}_{construction} = c\dot{X}'e$$

Next step consists in alter electricity generation structure by raising the participation of the source chosen and reducing more polluting sources. A new emission coefficient ($\tilde{c}$), less pollutant ($\tilde{c} < c$), can be determined and total pollution in the matrix is recalculated ($\tilde{P}_T$):

$$\tilde{P}_T = \tilde{c}X'e$$

Ecological payback is the required time of power plant operation to compensate total CO_2 emitted during its construction.

4. Data

Data for I-O matrixes are based on Brazilian national accounts for 2004 from IBGE and basic price matrixes were obtained through Guilhoto and Sesso Filho (2005) methodology. Matrix is divided into 41 sectors with an electricity generation sector which was divided into "Wind Power Generation" (according to O&M costs) and "Other Sources".

In order to determine electricity consumption, the distribution structure from EPE (2006a) was employed combined with BEN 2007 (MME, 2008) sector disaggregation. For 2004, it shows a total consumption of 350 TWh, from which 48% were allocated to industry and 22% to household. Final CO_2 emission relation for 2004 in relation only to electricity generation was estimated in 0.07117 tCO_2/MWh.

Data for wind power plants were based on Osorio Wind Park that reached full operation in 2007 with 150 MW installed (Table 3). For construction phase, expenses structure was estimated with information on total construction costs (R$ 650 million) and materials from Ventos do Sul Company (Ventos do Sul, 2007). They were allocated according to an international expenses average for wind farms (Winrock International, 2004).

O&M expenses were based on Tolmasquim (2005) which considers OPEX (Operational Expenditure) as 3.2% of turbines values. According to Dutra (2001), turbines maintenance costs vary between 0.8% and 1.3% of their value. For this study, a more conservative posture is adopted for O&M that comprises expenses with equipment, labor and other services in the plant.

Finally, as full Osorio integration in NIS was complete only in 2007, operating all year with firm energy (capacity factor of 30% approximately), generation data was taken from that year (ONS, 2008). Energy tariff was based on Normative Value of Aneel estimated by Dutra (2001) in R$ 118.59/MWh.

5. Results and Discussion

Energy intensity estimates (electricity consumption by added value) by sector highlights "Nonferrous Metals Metallurgy" sector with the highest intensity (4,678 MWh/R$$_{\text{added value}}$), and "Transportation" sector with the lowest intensity (13

MWh/R$$_{added\ value}$). “Trade” sector which had second biggest energy consumption after “Residential” sector showed low intensity (268 MWh/R$$_{added\ value}$).

From plant construction vector is possible to determine economic impacts and corresponding CO_2 emissions, or the ecological “cost” of plant built. As noticed in graph 4, most affected sectors were “Machinery and Equipment”, due to turbines manufacturing, “Steel and Products Manufacturing” and “Construction”.

Nevertheless, “Steel and Products Manufacturing” sector was responsible for the majority of CO_2 emissions (3,949 tCO_2), followed by “Nonferrous Metals Metallurgy” (2,570 tCO_2) and “Nonmetallic Mineral” (778 tCO_2), which sustains the characteristic of been the most energointensive sectors in the economy (Appendix A). Total emission during construction was 10,565 tCO_2.

In relation to employment, construction phase created 18,094 jobs (direct and indirect), and “Construction” sector alone has employed 4,219 jobs, followed by “Machinery and Equipments” with 2,781 jobs. This is consequence of an elevated employment coefficient in construction (35.7 jobs/R$ million) and large expenses in wind turbines produced in Brazil (49% of total investment). As all economy is considered in these estimates, job creation is higher than in international studies which consider only local impact.

Two simulations were developed to account total payback time of the wind power plants. First simulation states that the new plant replaces an existing thermo plant, which means that annual wind generation (558.93 GWh) replaces the same amount from a steam coal, natural gas or fuel oil power plant. Four scenarios were tested (tables 4 and 5).

Payback times were low in this simulation, ranging from 8 days when replacing most pollutant plants (steam coal), to 13 days, when replacing lowest pollutant plants (natural gas) (Graph 5).

Second simulation states that there is no changes in current power plants generation and the new wind plant is add to total electricity production (no replacement is done). In this scenario the marginal effect for pollution reduction is low (-0.16%) implying a payback time superior to the first simulation: 124 days or 4 months (Table 6).

6. Conclusions

Current energy scenario in Brazil is concerning, once internal energy offer expansion is inferior to demand requirements growth, which discrepancy can lead to another supply limitation similar to 2001 blackout. PAC plans some important projects in energy area, focused on the new global sustainability issue. Resources are directed to alternative energy sources, such as thermonuclear plants in response to raising environmental impacts from hydro power in Amazon region.

Despite the fact that Brazilian energy matrix is one of the “cleanest” and renewable in the world, sustainability issues have still important role in new power plants investment decisions. Even CO_2 emission free plants as solar and wind plants have environmental weight during construction by requiring inputs from the economy.

I-O methodology with ecological focus allows a more detailed analysis of interindustrial relations and their impact on environment, focusing on direct and indirect effects of construction and operation. Applied to wind power plants in Brazil, it shown a low level of pollution during construction, considering only electricity generation impacts, due to a concentrated energy matrix on non-pollutant hydro plants (88%).

Results analysis reinforce the “clean” energy characteristic of this type of plants, which has a CO_2 emissions payback inferior to one month, in case of replacing current polluting plants, or four months in case of generation adding only.

Future developments of this methodology can extend the comparative scope, considering other energy sources consumed by industry besides electricity and other types of power plants. Nevertheless, only society can decide which energy option shall be chosen to sector’s expansion, having in mind current environmental scenario and resources availability in Brazil.

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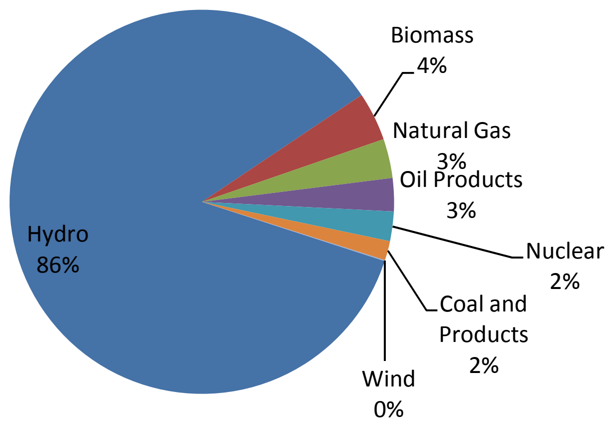
Graph 1 – Electrical Energy Structure, Brazil, 2007



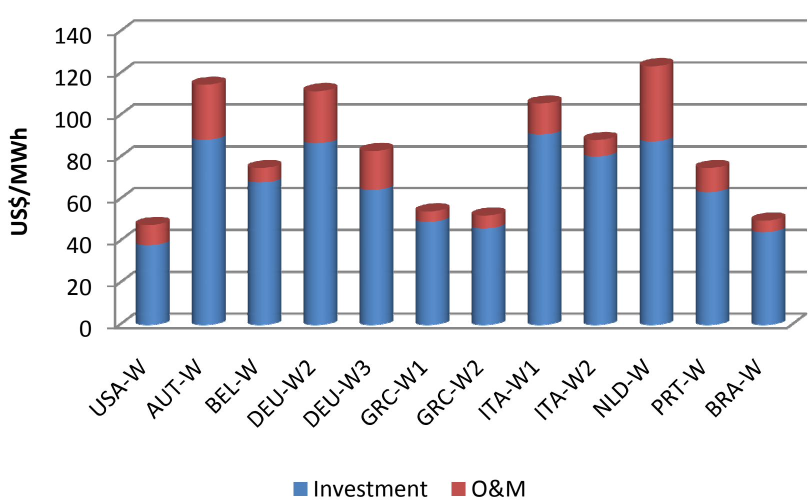
Source: MME. **Balanço Energético Nacional 2008 – Ano Base 2007**. Rio de Janeiro: EPE, 2008.

Table 1 – Greenhouse Effect Gases Emissions, Brazil, 1994

Origin	Communication	Estimations
Energy – Fossil Fuels	237	233
Energy – Biomass	-	192
Industrial Processes	17	-
Change in land and forest use	776	-
Total	**1.030**	**425**

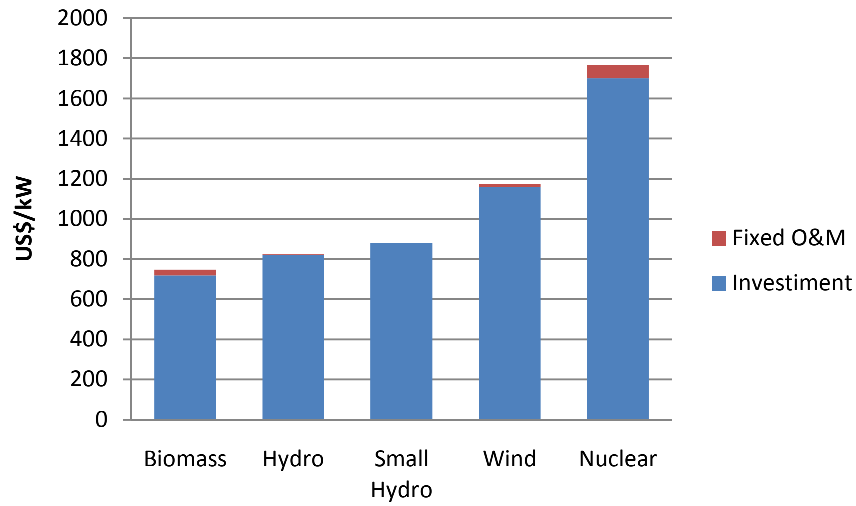
Source: Leite, 2007.

Graph 2 – Levelised cost of wind generated electricity at 10% discount rate (US$/MWh)



Source: NEA, 2005; Tolmasquim, 2005.

Graph 3 – Generation costs within power plants, Brazil



Source: Adapted from Tolmasquim, 2005.

Table 2 – Wind farm impacts, international studies

Location	Power (MW)	I-O Model	Total Jobs	Income* (Construction)
Lincon County	107	IMPLAN	39	US$ 98,000,000
Kittitas County	390	IMPLAN	238,8	US$ 11,000,000
Nebraska	800	IMPLAN	770	US$ 20,000,000
Cohocton	82,5	RIM II	641	US$ 385,360,000
Dutch Hill	42,5	RIM II	392	US$ 204,723,000

*Direct, indirect and induced effects

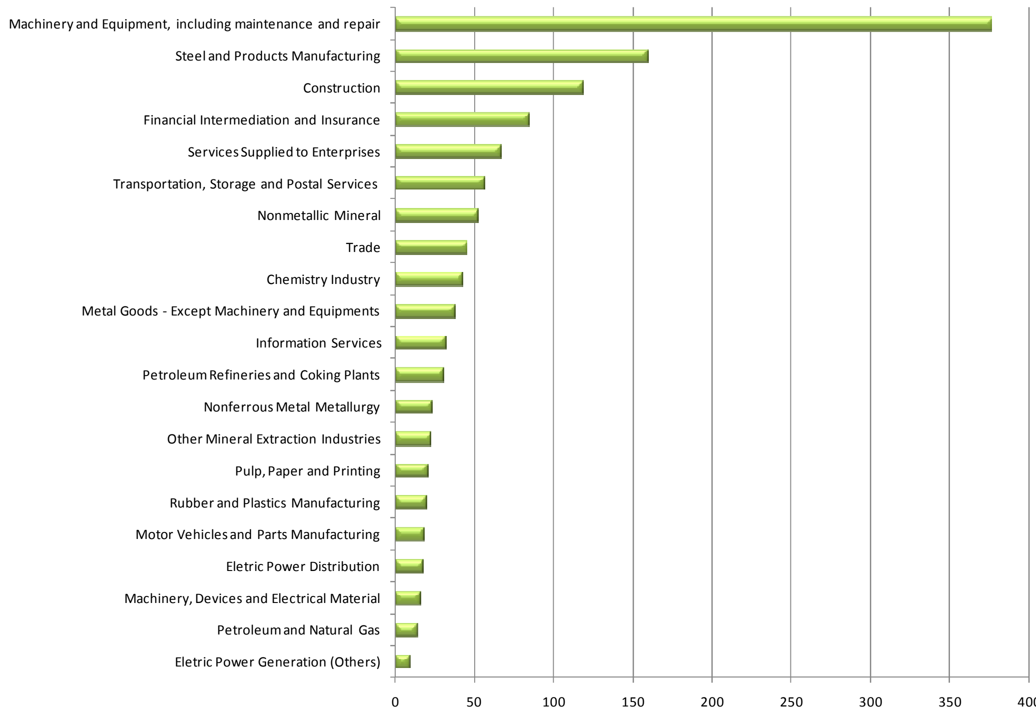
Sources: Saratoga Associates, 2006a; Saratoga Associates, 2006b; NREL, 2004.

Table 3 – Estimated Costs Structure in Osório Wind Farm (2004)

	Expenses %	R$ Million
Construction	22%	
Concrete		R$ 12,222,214.09
Steel		R$ 11,151,818.18
Iron		R$ 11,151,818.18
Civil Construction		R$ 112,874,149.55
		R$ 147,400,000.00
Towers	10%	
Concrete		R$ 19,223,288.18
Steel		R$ 47,776,711.82
		R$ 67,000,000.00
Interesting rates during construction	4%	**R$ 26,800,000.00**
High voltage substation/interconnection	4%	**R$ 26,800,000.00**
Development Activities	4%	**R$ 26,800,000.00**
Financing and Legal Taxes	3%	**R$ 20,100,000.00**
Project and Engineer	2%	**R$ 13,400,000.00**
Terrestrial Transportation	2%	**R$ 13,400,000.00**
Turbines	49%	**R$ 328,300,000.00**
Total	100%	R$ 670,000,000.00

Source: Ventos do Sul, 2007; Winrock International, 2004.

Graph 4 – Economic Impact by Sector (R$ Million)



Source: Research data.

Table 4 – Steam Coal and Fuel Oil Replacement

Source	Steam Coal		Fuel Oil	
	Generation %	tCO_2/Year	Generation %	tCO_2/Year
Natural Gas	4.20%	9,720,999	4.20%	9,720,999
Wind	0.18%	0	0.18%	0
Steam Coal	1.66%	6,818,079	1.81%	7,476,814
Firewood	0.00%	0	0.00%	0
Diesel Oil	1.96%	6,337,462	1.96%	6,337,462
Fuel Oil	0.40%	1,339,772	0.24%	801,039
Uranium on UO_2	3.32%	0	3.32%	0
Hydro	88.28%	0	88.28%	0
tCO2/MWh	0.06928		0.06962	
tCO2/year avoided	514,747		420,975	
% of Annual Reduction	2.65%		2.17%	

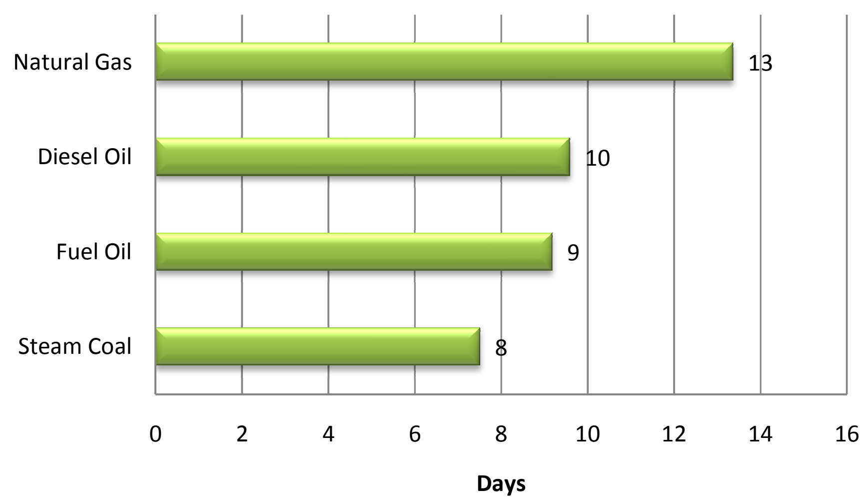
Source: Research data.

Table 5 – Diesel Oil and Natural Gas Replacement

	Diesel Oil		Natural Gas	
Source	**Generation %**	**tCO_2/Year**	**Generation %**	**tCO_2/Year**
Natural Gas	4.20%	9,720,999	4.04%	9,350,905
Wind	0.18%	0	0.18%	0
Steam Coal	1.81%	7,476,814	1.81%	7,476,814
Firewood	0.00%	0	0.00%	0
Diesel Oil	1.80%	5,821,708	1.96%	6,337,462
Fuel Oil	0.40%	1,339,772	0.40%	1,339,772
Uranium on UO_2	3.32%	0	3.32%	0
Hydro	88.28%	0	88.28%	0
tCO2/MWh	0.06969		0.07011	
tCO2/year avoided	403,019		289,198	
% of Annual Reduction	2.07%		1.49%	

Source: Research data.

Graph 5 – Payback time in each scenario



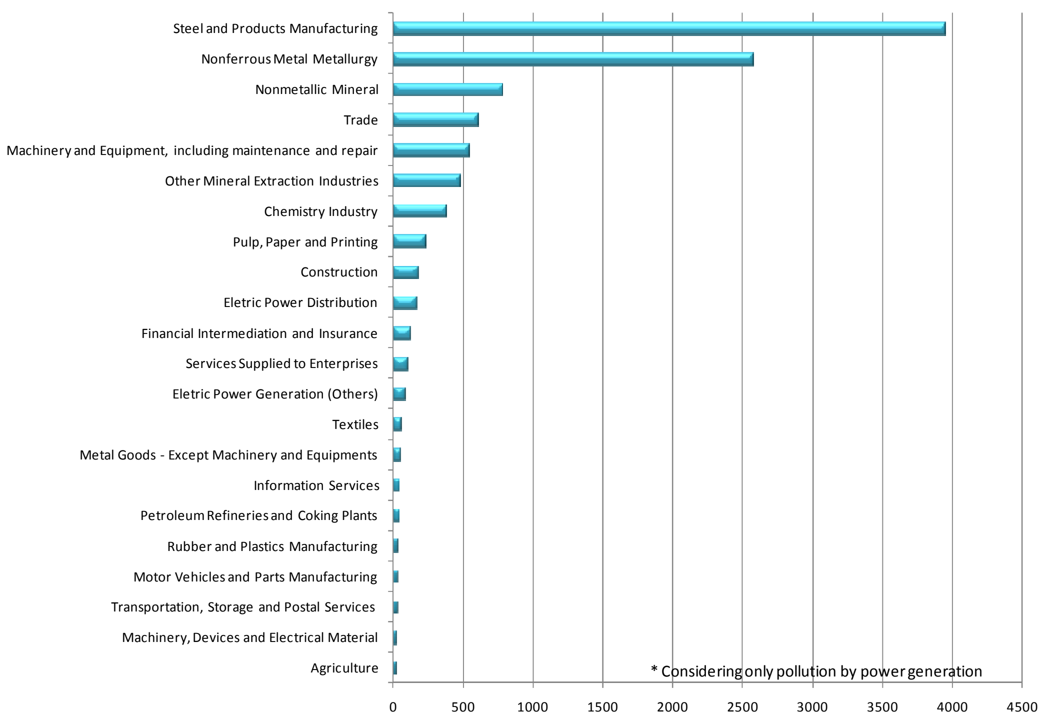
Source: Research data.

Table 6 – Wind Energy raise without generation replacement

Source	GWh	Generation %	tCO_2/Year
Natural Gas	14,681	4.19%	9,720,999
Wind	620	0.18%	0
Steam Coal	6,344	1.81%	6,818,079
Firewood	0	0.00%	0
Diesel Oil	6,868	1.96%	6,337,462
Fuel Oil	1,390	0.40%	1,339,772
Uranium on UO_2	11,611	3.32%	0
Hydro	308,584	88.14%	0
tCO2/MWh	0.07105		
tCO2/year avoided	31,032		
% of Annual Reduction	0.16%		

Source: Research data.

Appendix A – Pollution Emitted During Construction (tCO_2)



Source: Research data.