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Economic Model for Energy Planning: Evaluating the Impacts of  
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# A Social-Environmental Regional Sequential Interindustry Economic Model for Energy Planning: Evaluating the Impacts of New Power Plants in Brazil

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## Abstract

Energy planning is a multidimensional problem as it affects the economy, environment and local population in a spatially heterogeneous fashion. In this paper, we propose an integrated social-environmental economic model for energy planning analysis that estimates economic, emissions and public health impacts at different regional levels. By combining the traditional I-O framework with electrical and dispersion models, dose-response functions and GIS data, our model aims at expanding policy makers' scope of analysis and providing an auxiliary tool to assess energy planning scenarios in Brazil both dynamically and spatially. A case study for wind power plants in Brazil was performed and the results highlight the unbalance between economic benefits and negative health effects across the wealthiest and poorest regions in the country.

**Keywords:** Energy Planning, Input-Output Analysis, Regional Economics

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# 1 Introduction

The electrical sector is responsible for a considerable amount of greenhouse gases emissions worldwide, but is also the one in which modern society depends the most to maintain its living standards as well as the functioning of economic and social activities. Moreover, the Kyoto Protocol and IPCC (Intergovernmental Panel on Climate Change) reports on climate change identify sustainable development and rational use of resources as key focal points for the future. Thus, energy planning analysis should consider not only local economic impacts, but also environmental and social spillovers within and between regions during the entire life cycle of investments.

The Brazilian energy matrix is one of the least polluting in the world, mainly due to its domestic electricity supply, concentrated in renewable energy sources (79.3%). Nevertheless, the generation portfolio is not very diversified with predominant supply of hydropower plants (70.6%) and low shares of other “clean” sources such as biomass (7.6%), nuclear (2.4%) and wind (1.1%), which increase energy security issues EPE (2014).

Since 2003 an electric consumption rebound has raised average per capita growth rates to 5% annually in Brazil Tolmasquim (2005), which combined with income elasticities for electricity greater than one, has led to a surge in consumption exceeding the annual GDP growth and a mounting pressure for new power generation infrastructure. In order to comply with these new challenges, several projects have been undertaken in the last years, particularly new wind, gas-fired and thermonuclear plants ANALISE (2010).

Considering that 22% of all Brazilian greenhouse gas emissions derive from energy use MCT (2009) that includes the electricity sector, it is essential to discuss the externalities of energy sources chosen for the expansion of installed capacity. Variables such as the amount of pollution, power plant location and population density have diverse effects on public health and need to be accounted for during energy planning.

Several epidemiological studies highlight that even short term exposure to non-recommended levels of pollutants may lead to increases in mortality rates and development of different morbidities Pope (2000). Nevertheless, pollutants’ concentration varies across regions according to the location of emission sources, microclimate dynamics, topography, weather and other factors, confirming the importance of spatial analysis. Moreover, pollutants emissions and climate change have a reflexive effect both on the electricity system – affecting the efficiency of certain power plants at low air quality levels and higher intake temperatures – and in the local and national economy – due to demand shifts, lost working days and increase use of the health care

sector Schaeffer et al. (2008).

In sum, the current scenario leads to new discussions about electricity generation portfolios that must be expanded and diversified under the premise of environmental sustainability. Based on the latter, this study assess different power plants not only financially but also socio-environmentally, accounting for regional idiosyncrasies. The proposed model allows assessing externalities in different regions and advantages/ disadvantages of alternative sites for new plants. It is composed of a set of regional input-output matrices for Brazil and three other modules integrated computationally that evaluate environmental, energy and health impacts intra- and inter-regionally.

In the next section, we describe the proposed model, discussing each module separately. Section three explores the databases used and a case study for Osório Wind Farm is presented and analyzed in section four. Conclusions follow in section five.

## 2 Methodology

### 2.1 Overview

Impact analysis is an essential tool for policy making by providing *ex ante* evaluations on the effects of new projects, specially for large infrastructure investments. In the case of energy planning, *ex ante* evaluations are performed well before the beginning of a project (construction of power plants, substations and transmission lines) and involve assessing several scenarios, construction sites and their induced regional impacts. One must notice that, besides investment costs, economic multipliers, emissions and public health impacts differ spatially and a balance of positive and negative externalities should be considered in planning. Moreover, impact analysis allows addressing benefits and issues that different agents (decision-makers, enterprises, organizations and population) will perceive across regions.

The primary characteristic of large construction projects is its transient nature Romanoff and Levine (1980), i.e., economic shocks (demand of inputs) are heterogeneous through time. Their implementation, in particular power plants, extends throughout several months before completion. Moreover, construction is a complex sequential operation demanding different industrial and non-industrial inputs in subsequent phases. Hence, the analysis requires dynamic models to better capture short-term fluctuations in outcomes and should not rely on traditional static models<sup>1</sup>. As each project has unique

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<sup>1</sup>Traditional static economic models imply the comparison of before/after construction

costs, location and technology, distinct evaluations must be performed for every option and compared using a common unit of analysis.

The proposed model addresses the previous issues by combining a dynamic economic model with several socio-environmental extensions. It is divided into four interconnected components – (1) Core Economic Model; (2) Environmental Module; (3) Energy Module; and (4) Health Module – with a feedback loop that iterates the algorithm. The model relies on several georeferenced databases and a multiregional input-output matrix. Impacts are estimated with time and spatial dimensions providing a dynamic picture of benefits and losses of alternative construction sites for a power plant’s project and their regional externalities (Fig. 1).

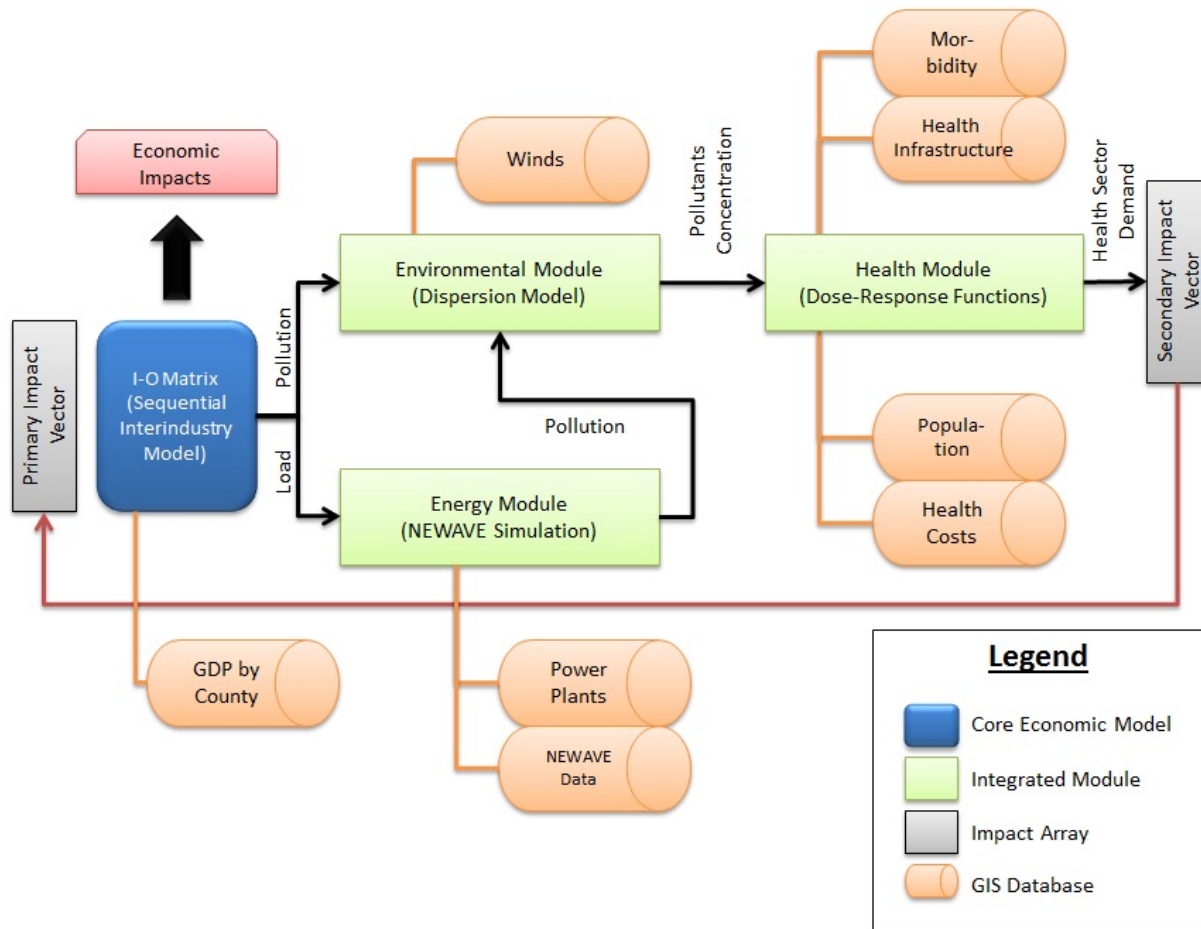
Using a regional Sequential Interindustry Model (SIM), direct and indirect economic impacts during construction of a power plant are estimated for each region. The advantage of using a SIM is the ability to analyze how irregular demand flows in different stages of construction dynamically impact the economy over several time periods. The required industrial output also raises the demand for electricity, which must be supplied with extra generation. The Energy Module emulates the grid operator’s wheeling system (based on the NEWAVE methodology) and is applied to determine which power plants will be dispatched and their additional production.

Next, based on pollution coefficients by industry and thermal power plant, we estimate total pollution generated by the economy and the spatial distribution of emissions. The latter serves as input to the Environmental Module which assesses the dispersion of pollutants and forecasts their concentration in each region. Finally, pollutants’ concentrations are analyzed in the Health Module, that estimates the demand for health services/products in different regions. This demand becomes a new economic shock for the Input-Output system that enters the process in an iterative fashion.

Georeferenced information is used in several databases, providing data on population density, wind speed and direction, public health services availability and existing power plants for each location. A spatiotemporal dynamical vision of the entire process is achieved allowing analysis of results in an aggregated way (economic, environmental and public health total impact) or disaggregated by region, thereby revealing more sensitive locations to pollution problems and/or economic benefits.

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steady states, thus neglecting the existing dynamics in-between these two time periods.



**Figure 1:** General Vision of the Model

## 2.2 Economic Module

The Input-Output (I-O) framework provides a detailed picture of both macroeconomic and microeconomic impacts of policy effects in a certain region through the analysis of industrial interdependency within an economy. The model is structured as a set of linear equations, each representing one sector's total production and its sales structure to the other sectors in the economy and final demand. Hence, every sector assumes a double role in the economy: buyer of required inputs and seller of its output. Although any single sector is directly connected to a just few others, all sectors are ultimately interconnected via indirect relations.

The model is derived from an input-output table (IOT), a dataset compiled annually from the system of national accounts that provides flows of commodities between sectors of the economy. Transactions are measured in terms of value, more specifically in basic prices<sup>2</sup>. The IOT accounts for every dollar “entering” the economy (domestically produced or imported) in a particular year and its “destination”, i.e., industrial consumption or final demand consumption (households, government, inventories, exports, etc.).

In the economy, the production of a good or service has two consumption destinations: either to be directly consumed by final demand or used as an input in the production of another good/service (intermediary consumption). Denoting by  $x_i$  sector  $i$ 's total production,  $z_{ij}$  the intermediate consumption of its production by  $n$  sectors of the economy ( $j = 1, 2, \dots, i, \dots, n$ ) and  $y_i$  final demand of sector  $i$ 's production, we have the following relation<sup>3</sup>:

$$x_i = z_{i1} + z_{i2} + \dots + z_{ii} + \dots + z_{in} + y_i \quad (1)$$

To derive the traditional demand-pull model, assume that the interindustrial flows from  $i$  to  $j$ , say, depend entirely on sector  $j$ 's total production in a certain time horizon. The technical coefficient ( $a_{ij}$ ) is, then, the relation between the share of sector  $j$ 's production used by sector  $i$  ( $z_{ij}$ ) and sector  $j$ 's total production ( $x_j$ ). It is assumed to be constant according to the premise of constant returns to scale Miller and Blair (2009), viz:

$$a_{ij} = \frac{z_{ij}}{x_j} \quad \forall i, j \quad (2)$$

Fixed technical coefficients imply a methodology limitation once the own economy dynamics causes coefficient variations over time and consequently, analysis and inferences are valid for a short term horizon Labandeira and Labeaga (2002). Entering equation 2 in 1, rearranging in matrix form and solving the equations to determinate total output required to supply final demand ( $y$ ):

$$x = (I - A)^{-1} * y \quad (3)$$

The Leontief Inverse,  $(I - A)^{-1}$ , conveys information on the total output requirement from each sector for a \$1 change in final demand, direct (from

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<sup>2</sup>Basic prices = consumer prices - (transportation margin) - (retail margin) - (net taxes)

<sup>3</sup>Notation: capital letters denote matrices, lower case letters denote vectors and lower case letters with subscripts denote a scalar. The vector  $\iota$  represents a unitary array of convenient dimensions.

final demand) and indirect (from intermediary demand). It reflects how final demand propagates inside the economy.

This I-O formulation, however, intrinsically assumes that production occurs simultaneously, i.e., time is compressed in a single time-step, which is inadequate for our purposes. Therefore, we use the Sequential Interindustrial Model (SIM), first introduced by Romanoff and Levine (1977), that is built on the static I-O model with the insertion of a time framework in industrial processes. The SIM is based on time-phased production, i.e., production processes occurs sequentially in time according to the schedule of each industry. Such flexibility allows representing different stages of manufacturing and transportation to final use, and assessing transient phenomena as the construction of power plants Romanoff and Levine (1981).

SIM assumes the time interval  $t$ : (1) to be equal for all industries and constant through time; and (2) that all industrial intervals are synchronized Romanoff and Levine (1981). Without these assumptions, it would not be feasible to formalize the model using difference equations and approach solutions that could be assessed using the traditional I-O framework. Recalling the fundamental relation expressed in equation 1 and assuming that time is partitioned into discrete industry intervals, during the  $t^{th}$  interval the I-O model can be rewritten as:

$$x_t = Z_t * \iota + y_t \quad (4)$$

Industries are categorized according to their production dynamics as anticipatory, just-in-time or responsive. In anticipatory mode, production starts at a time interval prior to demand (due to the extended length of the process (agriculture for instance) or ready-made standards goods (typical of many manufacturing)) in anticipation of future orders. In just-in-time mode, production starts and finishes at the same time interval as demand is realized, typical of services. And in responsive mode, production starts at the same time interval as orders are placed, but is delivered at a later time interval, typical of customized goods and construction. Hence, we have:

$$Z_t * \iota = A_a * x_{t+1} \quad (\text{anticipatory}) \quad (5)$$

$$Z_t * \iota = A_j * x_t \quad (\text{just-in-time}) \quad (6)$$

$$Z_t * \iota = A_r * x_{t-1} \quad (\text{responsive}) \quad (7)$$



Hence, each independent model is derived by inserting equations 5-7 into equation 4 and applying the double-sided Z-transform. However, as the economy is composed of all types of industries, a mixed model is used embedding the three production modes. This system may be formalized as:

$$x_t = A_a * x_{t+1} + A_j * x_t + A_r * x_{t-1} + y_t \quad (8)$$

Hence, the solution takes the form:

$$x_t = \sum_{s=-\infty}^{\infty} G_s(A_a, A_j, A_r) * y_{t-s} \quad (9)$$

Where  $G_s(A_a, A_j, A_r)$  is a matrix function that has all path gains by industries until time period  $t$ . The only difference between pure systems and the mixed one is the production chronology. In any of the former specifications, nonetheless, total estimated output is equal to that of the static I-O model.

This single region SIM can be converted to a multiregional model by considering the matrices in equation 8 as block matrices. Hence, for two regions ( $R_1$  and  $R_2$ ):

$$\begin{bmatrix} x_t^{R_1} \\ x_t^{R_2} \end{bmatrix} = \begin{bmatrix} A_1^{R_1 R_1} & A_1^{R_1 R_2} \\ A_1^{R_2 R_1} & A_1^{R_2 R_2} \end{bmatrix} \begin{bmatrix} x_{t+1}^{R_1} \\ x_{t+1}^{R_2} \end{bmatrix} + \begin{bmatrix} A_2^{R_1 R_1} & A_2^{R_1 R_2} \\ A_2^{R_2 R_1} & A_2^{R_2 R_2} \end{bmatrix} \begin{bmatrix} x_{t-1}^{R_1} \\ x_{t-1}^{R_2} \end{bmatrix} + \begin{bmatrix} y_t^{R_1} \\ y_t^{R_2} \end{bmatrix} \quad (10)$$

Two extensions are required to create the interface between industrial dynamics, pollutants' emissions and additional electricity load. (1) We define a vector of pollution coefficients ( $p$ ) as the total amount of emissions (tons) of a particular gas  $g$  released in the production of R\$ 1 million of output:

$$p^{R,g} = (\hat{x}^R)^{-1} * TP^{R,g} \quad (11)$$

Where  $TP^{R,g}$  is an  $n \times 1$  vector comprising total annual emissions of pollutant  $g$  discharged by each industry in region  $R$ . However, we remove the coefficient for the electricity sector, since its emissions will be estimated separately in the Energy Module, avoiding double counting. (2) We define a vector of energy intensity coefficients ( $e$ ) as the total electricity required (MWh) to produce R\$ 1 million of output:

$$e^R = (\hat{x}^R)^{-1} * CTE^R \quad (12)$$

Where  $CTE^R$  is an  $nx1$  vector with total annual electrical consumption for each industry in region  $R$ . Thus, energy intensity is measured by total energy divided by total production value, not just added value.

The Economic Model operates in two steps: first, it calculates total industrial output ( $\dot{x}^R$ ) induced by a given demand shock ( $\dot{y}^R$ ) via the regional SIM. These values are then converted into emissions in order to determine total pollutants released during production ( $\dot{p}_c^{R,g}$ ). The  $\dot{p}_c^{R,g}$  vector contains pollution released by industry in each region in each time period, and serves as one input for the Environmental Module (pollution by location). Total output is also used to determine the additional electricity load during production ( $\dot{e}_c^R$ ), by postmultiplying the diagonalized total production ( $\widehat{\dot{x}}^R$ ) by the energy intensity vector ( $e^R$ ). This vector contains electricity requirements by industry in each region in each time period and serves as input for the Energy Module (electricity by location).

### 2.3 Energy Module

The Energy Module simulates the grid wheeling operation under different hydrological scenarios. Due to the hydrothermal characteristic of the Brazilian grid, we use simulated monthly prices to determine thermal dispatch and generation/load equilibrium.

In pure thermal systems, the generation dispatch problem is to minimize costs (mainly fuel) subject to the static equilibrium of the grid and capacity restrictions (also observing factors such as losses, transmission limitations, startup costs, etc). Hence, power plants are dispatched by increasing operating costs until demand is met. This type of system is decoupled in time, i.e., operative decisions in time  $t$  do not affect costs in  $t + 1$ , and dispatch and supply availability can be evaluated independently ENGEORPS (1998a).

Conversely, in hydrothermal systems, reservoirs act as energy storage and are used to reduce fuel costs from thermal generation in dry seasons. Therefore, hydrological uncertainty and downstream configuration of plants pose a much more complex intertemporal problem to optimize<sup>4</sup>. The dispatch problem minimizes immediate and future operating costs under uncertainty, subject to grid equilibrium and transmission, generation and reservoirs capacity constraints. The system's operation is coupled in time since there is a trade-off between depleting reservoirs in  $t$  or storing water for future periods ENGEORPS (1998a). Moreover, differently from pure thermal systems,

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<sup>4</sup>Altering river flows also affects water availability for consumption, industrial use and commerce. Thus, the overall optimization problem is more complex than stated above.

dispatch and supply availability are intrinsically correlated, as maximizing supply reliability implies base-load all thermal units, while minimize operational cost implies relying solely on hydro plants for power supply (which decreases reliability). The tradeoff factor is, hence, to stipulate either an acceptable risk of deficit or a cost of deficit.

Given the above complexities of the Brazilian system, the National System Operator (ONS) conceived the NEWAVE model to stipulate monthly prices and determine thermal dispatch (see A). Due to hydrological seasonality, diverse regional microclimates and atmospheric dynamics uncertainty, forecasts of reservoirs inflows are generally inaccurate. The least-cost operation strategy is, hence, calculated by stochastic dynamic programming for a wide combination of possible reservoir states and hydrological trends. Based on historical series of streamflows since 1931, the system operation is simulated for a sample of 2,000 synthetic energy inflow sequences in a 5-year horizon and an energy shortage risk target of 5% per year ENGEORPS (1998c). Then, the monthly short-run marginal cost (SRMC) for each inflow series is calculated. By adopting a certain hydrological scenario, a thermal power plant is dispatched in a given month if its operation cost is lower than the system SRMC for that month ENGEORPS (1998b).

NEWAVE is a well-established model used since 1979 by ONS, but due to the large volume of non-publically available data required it will not be reproduced in our model. Our algorithm (Fig. 2), however, utilizes the output of the model (its SRMC table), power plant data and hydro generation to simulate the dispatch under different hydrological scenarios.

After choosing a weather scenario, its water inflow pattern determines the hydro generation and the SMRC is stipulated for each month. From the SMRC, power plants are dispatched according to their inflexibility and operational costs, i.e., all plants with cost below the SMRC are dispatched. This determines the steady-state of the system and the generation share of each plant. As the additional monthly load induced by the industrial output is quite marginal compared to the baseload and available capacity, it does not require new plants to come online. Therefore, extra generation is supplied by currently dispatched plants and it is done proportionally to the share of total generation per plant. Pollution from dispatched thermal plants is estimated and used as another input to the Environmental Module (total emission, location and time period).

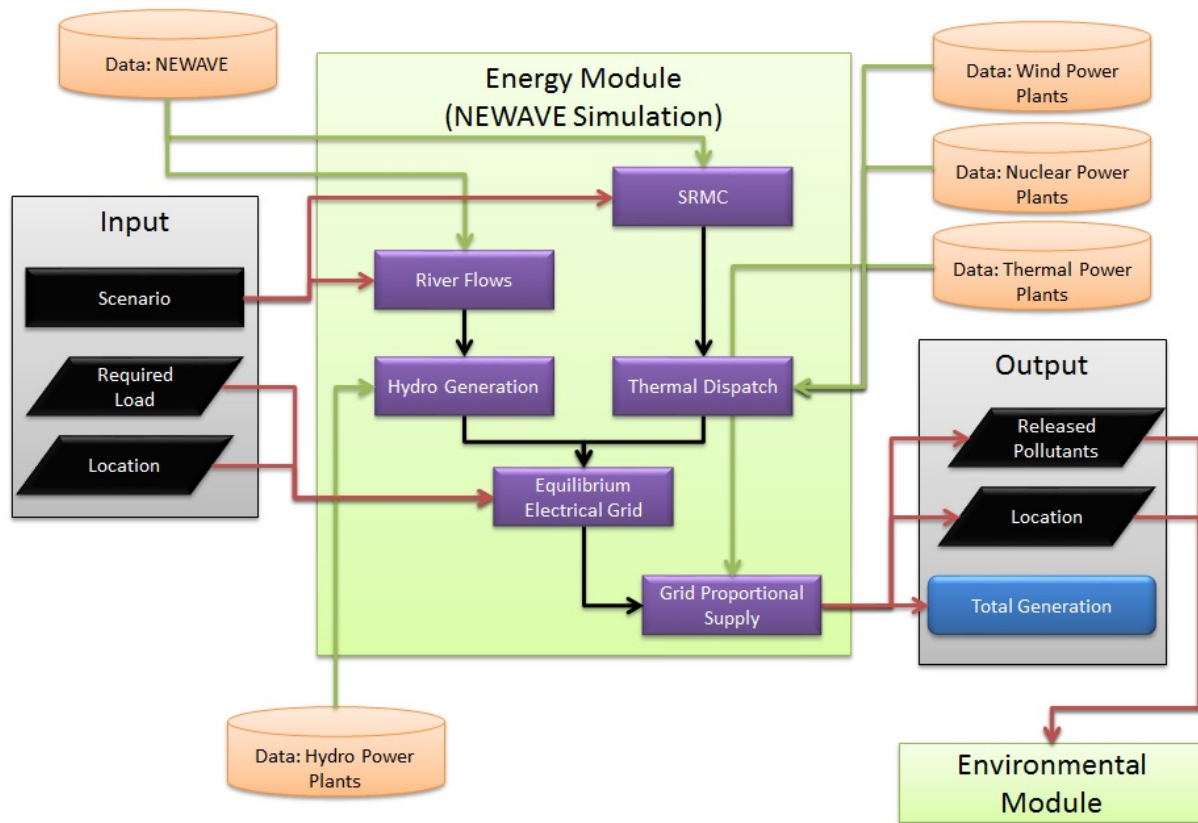
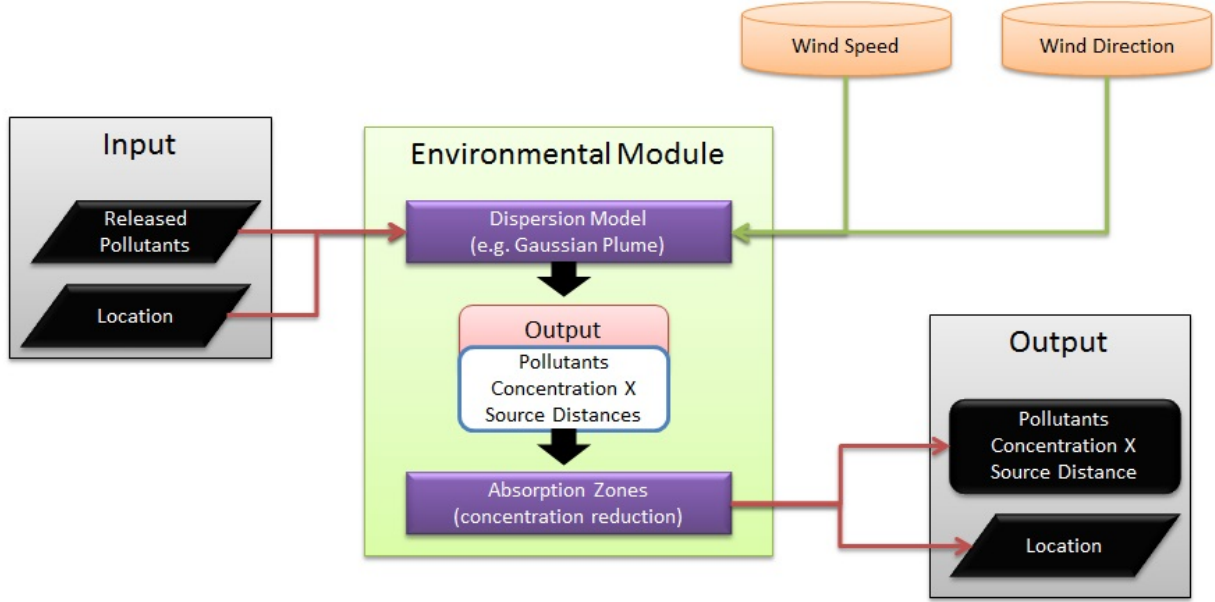


Figure 2: Energy Module

## 2.4 Environmental Module

Both Economic and Energy modules pollution outputs (quantity of pollutants released to the atmosphere, type and the location of the source by time period) are processed in the Environmental Module (Fig. 3). Using GIS data for meteorological conditions, a Gaussian Plume Model (GPM) is applied in each region to determine the total concentration of pollutants at different distances from their sources, considering the spillovers of one region to another.

Pollutants are carried by wind and diluted by atmospheric turbulence until final deposition on the ground. Some compounds may react in the atmosphere and form secondary pollutants like  $H_2SO_4$  and  $O_3$ . As this study only assess primary pollutants, that are chemically stable close to the



**Figure 3:** Environmental Module

emission source, a simple GPM (without any extensions that account for chemical reactions) is employed to predict their concentrations. The model assumes that continuously released air pollutants are carried in a straight line and mix with the surrounding air horizontally and vertically, resulting in a normal spatial distribution of pollutant concentrations European Commission (2005). We consider a homogeneous emission rate throughout the time period and concentration at ground level. It is formalized as:

$$c_t(d_t, l_t, g_t) = \frac{Q}{2\pi u \sigma_g \sigma_l} \left\{ \exp\left(\frac{-(g_t - h)^2}{2\sigma_g^2}\right) + \exp\left(\frac{-(g_t + h)^2}{2\sigma_g^2}\right) \right\} \left\{ \exp\frac{-l_t^2}{2\sigma_l^2} \right\} \quad (13)$$

Where  $c_t(d_t, l_t, g_t)$  is the atmospheric concentration at any point  $d$  meters downwind of the source,  $l$  laterally from the centerline of the plume and  $g$  meters above ground level;  $Q$ : emission rate;  $u$ : wind speed;  $h$ : stack height;  $\sigma_l$ : cross wind standard deviation (measure of plume width); and  $\sigma_g$ : vertical standard deviation. For the plume to dislocate in the air in a straight line at constant speed, two other assumptions are made: 1) flat terrain and 2) constant meteorological local conditions. Moreover, vertical wind shear is not considered. This model can assess the concentration of pollutants as far

as 100 km from the emission source Salby (1996).

The GPM will be used to estimate concentrations due to industrial and power plant emissions. Considering the coordinates of the source, wind speed and bearing in different seasons, the final output of the model is a matrix of concentration of pollutants by distance from the source at several time periods.

## 2.5 Health Module

The Health Module uses the pollutants' concentration data with space-time dimensions, to estimate health impacts and costs (Fig. 4). Adding it to pre-existing pollution on site at time period  $t$ , total pollutants concentration ( $pc_t$ ) can be estimated by region. Then, deleterious effects are forecasted through dose-response functions (DRF) which determine the increased probability of pollution-related diseases (morbidity rates) and estimate the health sector demand caused by this non-recommended exposure. DRFs relate the concentration of pollutants to which an agent has been exposed, to the physical impact on him. Following the discussion by Pope (2000), we consider that the DRFs do not have any threshold point. The impacts of  $\text{NO}_2$  and  $\text{SO}_2$  are assumed to increase indirectly from the particulate nature of nitrate and sulfate aerosols, and  $\text{CO}_2$  impact is measured by CO effects (which derives from an inefficient combustion of  $\text{CO}_2$ ).

To convert public health effects into demand for health care services, we use the average cost of treatment per patient admitted in public hospitals in region  $R$  for a particular disease  $D$  ( $cost_D^R$ ), multiplied by the previous hospital admission rate ( $admis_{D,t-1}^R$ ). The additional health care demand ( $h_t^R$ ) is calculated by estimating the number of excess diseases due to the pollution ( $admis_{D,t-1}^R * DRF(\cdot)$ ) and multiplying it by the treatment cost for each disease. Hence, it depends on the current number of hospitalizations, the increase in morbidity cases and the local treatment cost, as follows:

$$h_t^R = admis_{D,t-1}^R * DRF(pc_t^R) * cost_D^R \quad (14)$$

Notice, nonetheless, that increase in morbidity in a given region may not be fully reflected in an increase in health demand for that region as availability and capacity of health facilities vary. Hence, we assume that population may migrate to nearby regions seeking treatment. Finally, total health care demand is estimated and transformed into a new shock vector which iterates the model.

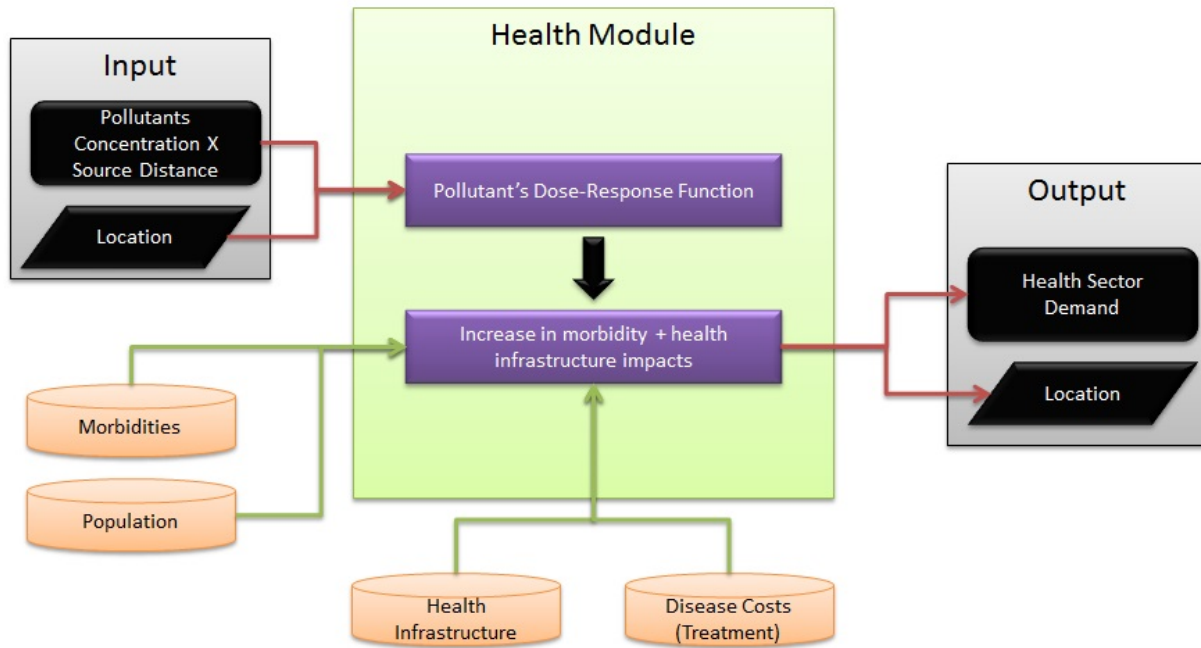


Figure 4: Health Module

### 3 Databases and Implementation

The national I-O matrix for Brazil was derived following the methodology proposed by Guilhoto and Sesso Filho (2005a) and the estimation of the interregional I-O system made according to Guilhoto and Sesso Filho (2005b). The 2004 matrix is divided into 12 sectors and 27 regions (26 states and Brasília). This level of aggregation was necessary to match industries with emission data from MCT (2009). In further analysis, more disaggregated data could be used.

In order to create a mixed SIM, the sectors were classified into responsive and anticipatory production modes. As highlighted by Romanoff and Levine (1986), anticipatory mode is usual in sectors such as agriculture, mining and manufacturing industries, in which production typically anticipates orders with readymade standard products. Responsive mode, on the other hand, is a characteristic of construction, ordinance, services and industries in contract research and development work, once they usually respond to custom orders, according to costumers' specifications. Sectors and their classification can be seen in B. Moreover, the time step  $t$  is taken as monthly intervals.

The database for the Energy Module is based on ONS (2010) and ANEEL (2005) information on power plants (location, generation capacity, costs and type of fuel). Data from ONS (2010) for 2004 is used to calculate the average capacity factor by plant in each month. Moreover, average generation was estimated for each plant from weekly reports also from ONS. The latter, however, is based on 2007 reports due to unavailable reports for 2004. NEWAVE’s databases were provided by Dorel (2011) and include SMRC matrices for 2006-2008 and water inflows in each period (1931-2006). Finally, energy coefficients by industry type were estimated with ECEN (2010) data regarding 2004 consumption. In that year total industrial and commercial consumption amounted to 310,017 GWh and households 86,695 GWh. Coefficients can be seen in table 1 below.

**Table 1:** Electricity consumption coefficients by industry

Industry	MWh/R\$ Million
Agriculture	80.90
Mining	198.39
Iron and Steel Industry	245.26
Chemical Industry	85.80
Cement Manufacturing	597.06
Nonferrous Metal Metallurgy (mainly aluminum)	1,781.01
Other Industries	104.60
Electric Power Sector	137.14
Air Transportation	-
Truck Transportation	-
Transportation - Others	23.68
Other Sectors	53.08

Source: Based on ECEN (2010).

In the Environmental Module, emissions by power plant type are gathered from ONS (2010) and ANEEL (2010) which provide information regarding the type of fuel, nominal power, geographic coordinates and municipality where the facility is located (besides population density). This level of detail allows a more accurate analysis of pollutant concentration and public health effects. Emission coefficients for each type of power plant regarding different pollutants were estimated based on ECEN (2010) with data from the National Energy Balance for 2004 and results can be seen in table 2. In our model, however, only CO and NO<sub>2</sub> levels will be assessed.



**Table 2:** Power plants emissions by type, Brazil, 2004 (kg/MWh)

Power Plant Type	CO <sub>2</sub>	CH <sub>4</sub>	CO	N <sub>2</sub> O	NO <sub>2</sub>
Biomass (Firewood)	633.87	0.14	11.32	0.03	0.85
Biomass (Sugar Cane)	634.64	0.26	14.80	0.03	0.58
Biomass (Others)	349.94	0.01	0.47	0.01	0.76
Coal	1,043.39	0.01	0.16	0.01	9.71
Diesel Oil	741.47	0.04	3.66	0.01	13.35
Fuel Oil	642.31	0.01	0.13	0.00	1.68
Hydropower	-	-	-	-	-
Natural Gas	498.37	0.05	0.38	0.00	1.60
Nuclear	-	-	-	-	-
Wind	-	-	-	-	-

Source: Based on ECEN (2010).

Nonetheless, there are no available databases with location of industries limiting the scope of the analysis. To overcome this gap, based on the economic structure of a state (from the I-O matrix), each municipality within that state is allocated a share proportional to its industrial GDP, and industries are homogenously distributed throughout its limits. Data from industrial GDP is taken from IBGE (2010). CO<sub>2</sub> emissions are estimated based on individual coefficients for each industry type, based on MCT (2009) for 2004 pollution. The only sector without emissions is the “Electric Energy Sector” to avoid double counting in the Energy Module. In order to obtain CO and NO<sub>2</sub> levels, based on data for 2004 from ECEN (2010), two additional conversion coefficients were set: 1 ton CO<sub>2</sub> = 0.0128 ton CO; and 1 ton CO<sub>2</sub> = 0.0028 ton NO<sub>2</sub>.

Moreover, for simplification, we assume the terrain in Brazil is flat to avoid the need of additional appendices to the GPM. GIS information regarding wind speed, bearing and latitude/longitude at municipal level is available from CEPTEL SWERA (2010) for 10km x 10km cells. This database refers to simulations generated in MesoMap for 360 days from a period of 15 years of data with each month and season being considered in a representative way. The determination of the appropriate mixing height is a complex task with several techniques proposed in the literature to estimate its value. The main issue is the sensitivity of the model’s results to its parametrization as shown in Brizio and Genon (2005) and European Commission (2005). Nonetheless,

for our simple case study for Brazil, we assume a stack height of 50m<sup>5</sup>.

The most comprehensive available emission data for Brazil covers CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFC-23, HFC-134, CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub> and CF<sub>6</sub> MCT (2009). But detailed disaggregation is provided only for the first three pollutants. Therefore, carbon dioxide, methane and nitrous oxide can be analyzed. Methane is not a toxic gas, hence, its health effects will be neglected. Carbon dioxide is evaluated through CO impacts and nitrous oxide is measured as nitrogen oxide. The DRFs used in this work are based on Gouveia et al. (2006) study and are summarized in table 3. In their study the sample is divided into children and elderly but we use a conservative number to represent an average adult response.

**Table 3:** Increase in morbidity due to 10  $\mu\text{g}/\text{m}^3$  raise in NO<sub>2</sub> and CO concentrations

	NO <sub>2</sub>	CO
Asthma	2.3%	5.4%
Pneumonia	0.8%	3.9%
Other Respiratory Diseases	1.2%	2.4%
Cardiovascular Diseases	1.0%	1.6%

Source: Adapted from Gouveia et al. (2006).

In order to convert public health effects into demand for health care services, the average cost per patient admitted in public hospitals (SUS System) is considered. Although private health care providers exist, the majority of the Brazilian population (90%) still relies on public health services. Moreover, as industries and power plants with high emissions are usually located in peripheral urban areas, low income population is more susceptible to suffer from pollution effects. Hence, data from SUS is a good approximation to the real health costs incurred. SUS (2010) has a large database with the number of hospital admissions by disease, total treatment cost, hospitalization period, mortality rate, etc., by Federal, state and municipal levels for the SUS system. This database is used to assess public health impacts.

The model was programmed in Pascal language using Borland Delphi 5 environment and the final software is entitled EPSIM (Energy Planning

<sup>5</sup>The model was also simulated with a stack height of 100m with fairly similar results in terms of overall health dynamics, although with reduced total costs. In terms of the full model, however, this variation did not change the main results nor policy implications.

Sequential Interindustry Model). The program was built in five different units (four modules and an iteration routine) and operates at both the state and municipality levels (27 states and 5,560 municipalities). In this initial version (implementation 2.1), it was designed to evaluate impacts for the construction phase only.

## 4 Case Study

### 4.1 Scenario

This case study is based on the Osório Wind Farm located in Rio Grande do Sul (RS), Brazil. Data for this wind power plant was based on Osório Wind Park that reached full operation in 2007 with 150 MW installed. Expenses during construction were estimated with information on total costs (R\$ 670 million) and materials from Ventos do Sul Energia (2007). They were allocated according to an international cost breakdown average for wind farms Windrock International (2004) (C).

In order to illustrate the model usage, a comparison is made between three Brazilian states suitable for wind farms investments: Rio Grande do Sul (RS), Ceará (CE) and Rio Grande do Norte (RN). We denote these states as "primary states". We assume the same construction demand and schedule (18 months) in all scenarios starting in January. We ran the model for both 1955 and 1983 hydrological trends (the driest and the wettest conditions respectively). This simple case study is intended to exemplify the type of impact analysis the model produces, and to address convergence and results compatibility.

### 4.2 Results and Discussion

A summary of results for economic, energy, environmental and health impacts is shown on table 4 below. Overall, results confirm the importance of assessing impacts in both spatial and temporal dimensions, once regional idiosyncrasies imply different effects for each scenario. Although both 1955 and 1983 hydrological trends were estimated, we will focus on the driest year (1955) since it represents the worst condition for the electrical system (high thermal supply).

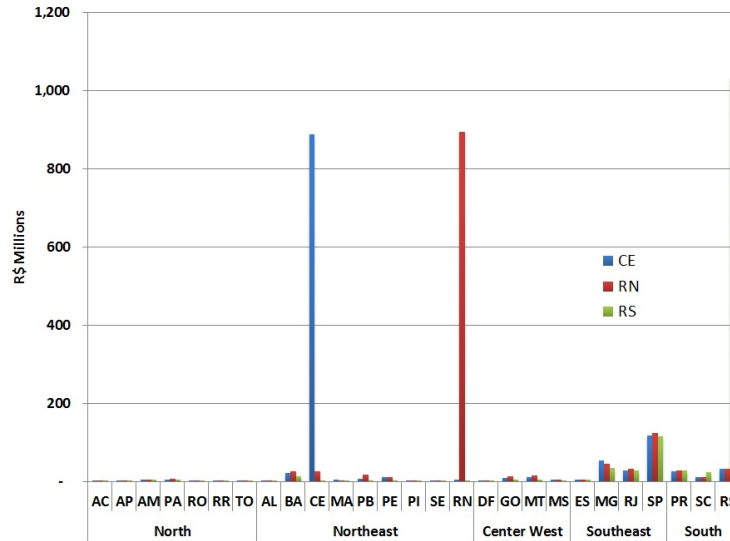
Total economic impact (direct and indirect) induced by construction in RS and RN are quite similar (R\$ 1,319 million and R\$ 1,310 million respectively), since the overall regional output multipliers in these states are close. However, as RS has larger intraregional and interregional multipliers with

**Table 4:** Summary of results for each scenario

	Dry Scenario			Wet Scenario		
	CE	RN	RS	CE	RN	RS
<b>Economic (R\$ Millions)</b>						
Direct Impact	670.00	670.00	670.00	670.00	670.00	670.00
Indirect Impact	588.41	639.76	648.99	588.38	639.73	648.97
<b>Total Impact</b>	<b>1,258.41</b>	<b>1,309.76</b>	<b>1,318.99</b>	<b>1,258.38</b>	<b>1,309.73</b>	<b>1,318.97</b>
<b>Employment</b>						
<b>Total</b>	<b>41,495</b>	<b>51,416</b>	<b>27,620</b>	<b>41,494</b>	<b>51,415</b>	<b>27,619</b>
<b>Electricity (MWh)</b>						
<b>Total Requirement</b>	<b>142.4</b>	<b>149.4</b>	<b>153.6</b>	<b>142.4</b>	<b>149.4</b>	<b>153.6</b>
<b>CO Emissions (Tons)</b>						
Industries	1,861.61	1,977.28	2,022.24	1,861.57	1,977.27	2,022.23
Electricity Sector	13.17	13.82	14.21	1.50	1.57	1.62
<b>Total</b>	<b>1,874.77</b>	<b>1,991.10</b>	<b>2,036.45</b>	<b>1,863.07</b>	<b>1,978.84</b>	<b>2,023.85</b>
<b>NOx Emissions (Tons)</b>						
Industries	407.23	432.53	442.37	407.22	432.53	442.36
Electricity Sector	95.49	100.23	103.06	23.07	24.22	24.90
<b>Total</b>	<b>502.72</b>	<b>532.76</b>	<b>545.43</b>	<b>430.29</b>	<b>456.75</b>	<b>467.27</b>
<b>Morbidity (Nr of cases)</b>						
Asthma	1,043	395	450	1,042	394	449
Pneumonia	3,011	2,080	2,342	2,989	2,057	2,318
Other Respiratory Diseases	370	216	285	369	215	284
Cardiovascular	2,096	1,360	1,785	2,092	1,356	1,781
<b>Treatment Cost (R\$ Millions)</b>						
Asthma	0.54	0.22	0.25	0.54	0.22	0.25
Pneumonia	2.50	1.78	2.04	2.48	1.76	2.02
Other Respiratory Diseases	0.39	0.21	0.28	0.39	0.21	0.28
Cardiovascular	0.67	0.44	0.56	0.67	0.44	0.56
<b>Total</b>	<b>4.09</b>	<b>2.65</b>	<b>3.13</b>	<b>4.08</b>	<b>2.63</b>	<b>3.11</b>

SP and MG than RN does, total economic impact was slightly higher in the former. In the case of CE (R\$ 1,259 million), lower output multipliers imply reduced effects in comparison to the other scenarios.

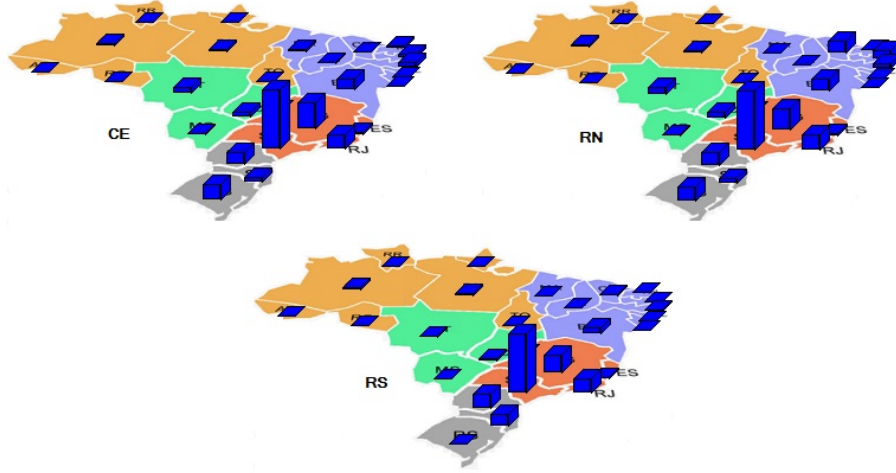
Regarding economic spillovers, one may notice that effects for RS scenario are concentrated in the South and Southeast regions, while for CE and RN scenarios, impacts are also observed in the Northeast region but major economic leakages are still located in the Southeast region (Fig. 5 and 6). This reflects the industrial structure of each region, once South and Southeast states concentrate around 78% of the 2004 industrial GDP IBGE (2010) and are the major supplier of the Northeast region.



**Figure 5:** Total Economic Impact by State and Scenario

Moreover, results also corroborate the fact that the states of SP, MG and RJ are the most important industrial suppliers in the country, serving as major outputs hubs, due to their industrial and service structure, which represents 53.7% of the national GDP IBGE (2010), and strong interregional links with all other states.

Direct and indirect jobs created also reflect the scope of the economic spillovers. They are higher for CE and RN in comparison to the RS scenario due to regional idiosyncrasies regarding labor intensity between Northeast and South/ Southeast states. Although hub states in the Southeast region are affected in all three scenarios, CE and RN also have major effects on neighboring Northeast states, which tend to be more labor intensive, while



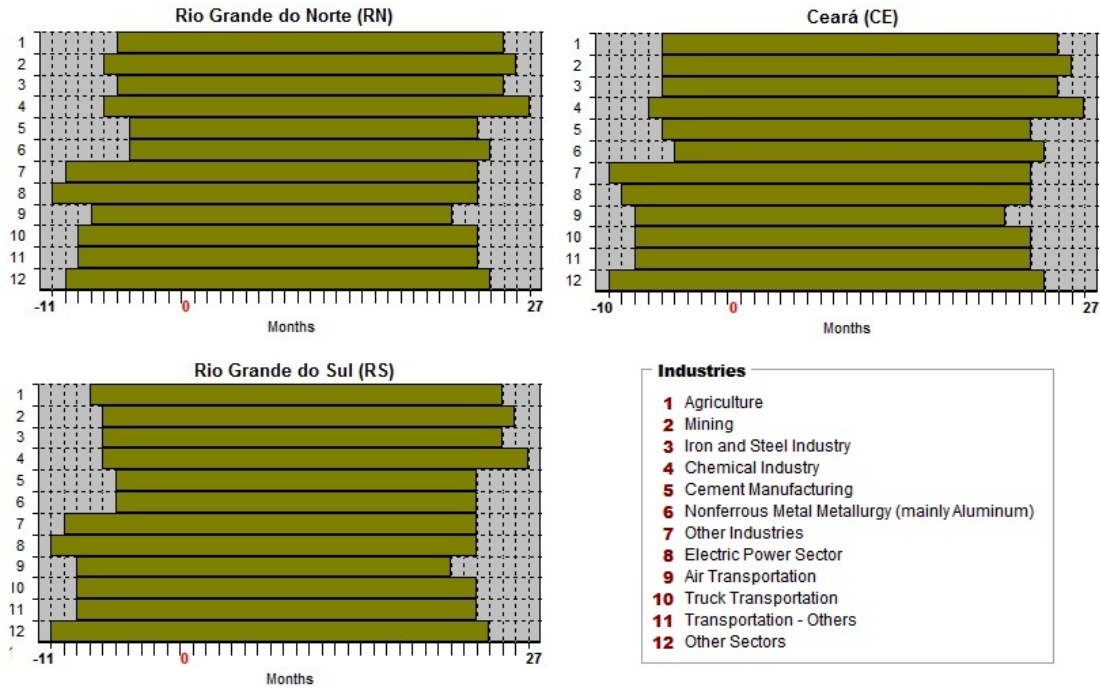
**Figure 6:** Distribution of Economic Spillovers by Scenario

RS impacts mainly capital intensive states (D). Moreover, most jobs are created during the construction interval and “Agriculture”, “Iron and Steel Industry”, “Other Industries” and “Other Sectors” concentrate employment generation in all three scenarios (E).

In relation to industrial activation through time, in all scenarios three sectors were demanded before all others: industries not directly related to civil construction, electricity companies and services (“Other Sectors” mainly), since the construction demand in the first months ( $t = 0$  and  $t = 1$ ) is strictly related to engineering consulting services and expenses prior to construction (Fig. 7). On subsequent time periods, “Mining”, “Iron and Steel Industry”, “Chemistry Industry” and “Cement Manufacturing” are continuously demanded until the end of the construction stimulus. The wider activation time of these sectors is due to the anticipatory production mode assumed. One may also observe a propagation effect beyond the initial 18 months of construction as a result of economic inertia.

Electricity consumption due exclusively to the construction of the power plant was estimated as 153.6 GWh for RS scenario, 149.4 GWh for RN scenario, 142.4 GWh for CE scenario. The energy requirements pattern is directly related to industrial activation due to economic impacts in each state, as can be noticed by comparing figures 5 and 8. These electricity requirements are in line with the ONS database, representing less than 1% of total electricity consumption in 2004.

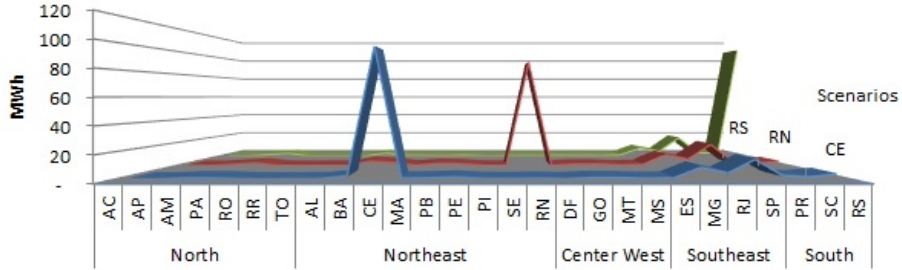
Total CO and NO<sub>2</sub> emissions are shown in table 4 and are also related to



**Figure 7:** Industrial Activation Through Time

total economic impact and energy requirements. Notice that although a large portion of emissions are concentrated in the primary state, pollution also spreads to other regions, particularly in Southeast states. For CE and RN scenarios, this negative externality has a particular pattern generating some emissions in neighboring states but most of it concentrates in the Southeast region, particularly in SP, MG and RJ (Fig. 9). RS emissions also exhibit the same effect; however, RS internalizes more industrial emissions (74.8% of CO emissions) and spreads more negative externalities to neighboring states than distant states (F, G and H). NO<sub>2</sub> emissions have similar distribution patterns.

Regional idiosyncrasies also influence health impacts in each scenario. Despite the fact that economic impacts and total emissions are higher in RN and RS scenarios than in CE's, increases in morbidity and total health costs are larger in the former due to the spatial distribution of pollution. First, CE has the second highest morbidity rate and the most expensive treatment costs for asthma, pneumonia and other respiratory diseases in the Northeast Region. As local CO emissions account for 68% of total emissions, most of



**Figure 8:** Electrical Requirement by State and Scenario

the increase in hospital admissions occurs in CE resulting in higher treatment costs.

Secondly, as can be seen in F, G and H, CE and RN have large emission leakages to states in the Northeast, Southeast and South regions. However, in relation to RN, CE creates higher pollutant concentrations in PE, MA and PI – states with high morbidity rates and treatment costs in the Northeast –, while RN affects predominantly other Northeastern states with cheaper treatment costs. Conversely, in relation to RS, CE’s higher morbidity rate is due to a much wider spread in emissions than the former, as highlighted before, and larger concentrations in MG, which has the second highest morbidity rates among all other states.

Moreover, there are significant timing differences regarding when health care resources must be mobilized to meet this demand. For RS, there is a defined peak in health costs at  $t = 7$  and  $t = 14$ , while CE and RN concentrate expenses during  $t = 4$  to  $7$  and exhibit a peak at  $t = 15$  (Fig. 10).

Finally, it is important to highlight the differences in disease prevalence in distinct time periods for each scenario (Fig. 11). Note, the seasonal effects on morbidity rates have a significant impact on diseases’ profiles. Due to major health impacts concentrated in the primary states, environmental conditions such as climate, population density and pre-existing pollution lead to an important distinct profile, especially for pneumonia, between northeastern states (CE and RN) and southern states (RS). Therefore, specific health treatments are demanded uniquely in time and in each scenario.



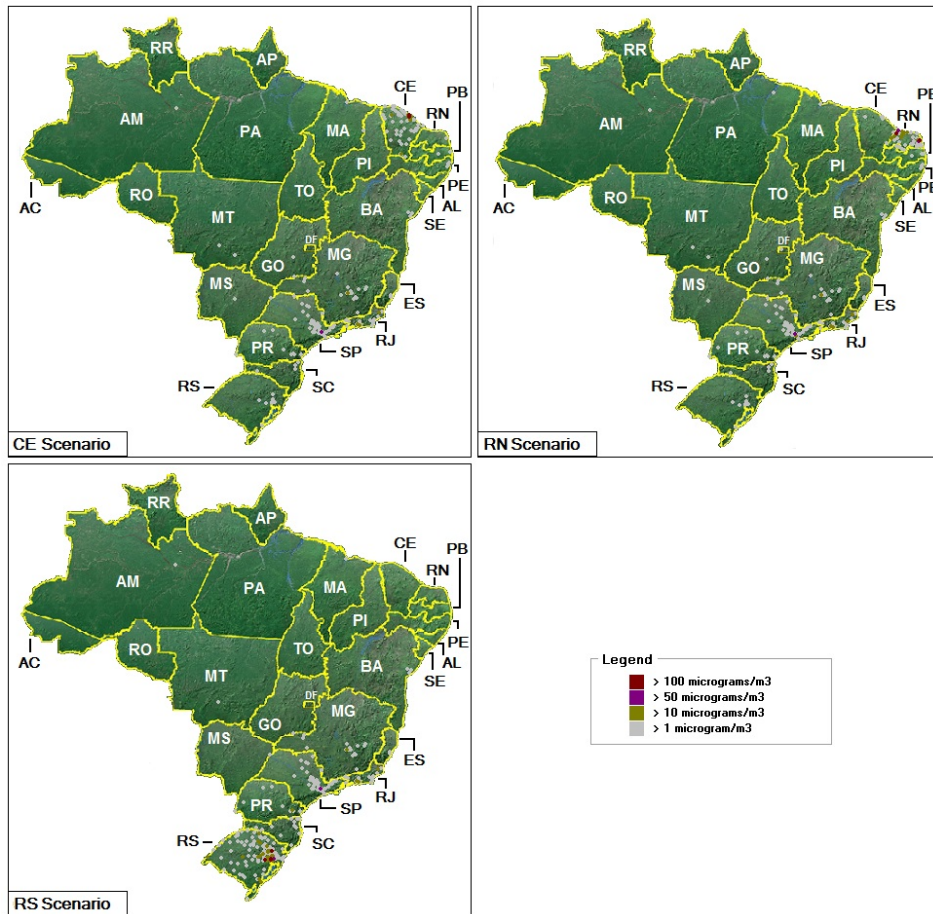


Figure 9: Total CO Concentrations by State and Scenario

## 5 Conclusions

As pollution is spatially dynamic - i.e. it is emitted at the source but its impacts extend to the length of dispersion it produces - to properly evaluate its externalities, models coupled with spatial components should be used. In this study, a hybrid top-down/bottom-up model is proposed, combining a regional economic model with GIS data and electric-social-environmental specifications. For each power plant site, the model estimates total economic impacts, effects on the wheeling dynamic of the electric grid and public health impacts due to pollution dispersion. Our model allows the comparison of different locations for the construction of new power plants in terms of

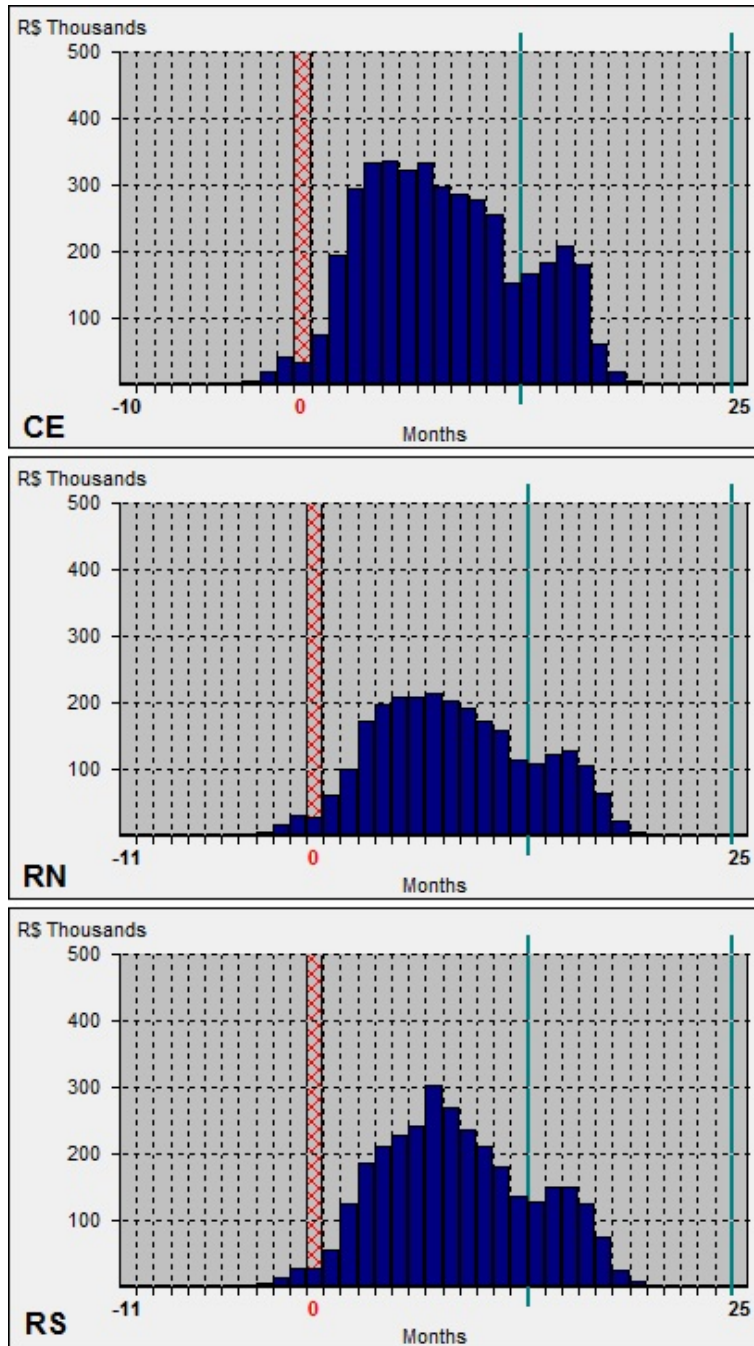
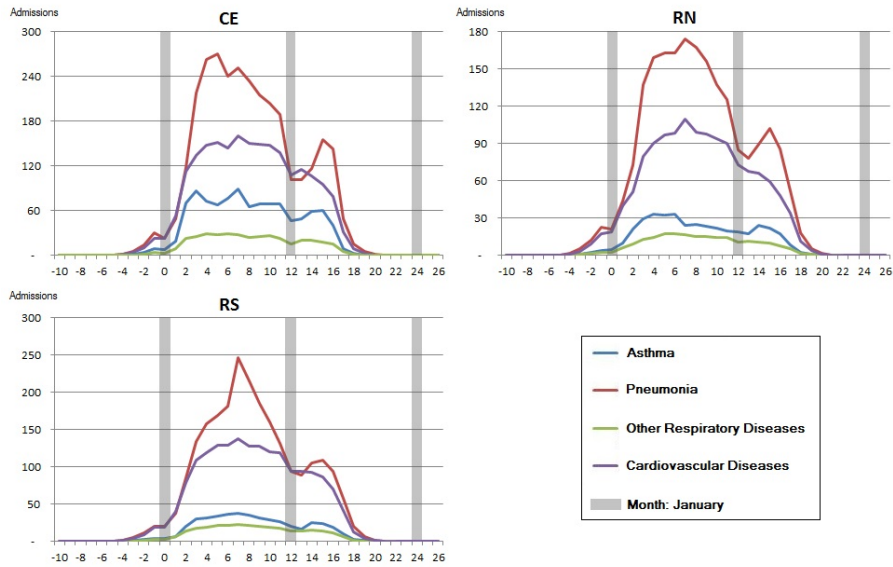


Figure 10: Health Care Demand Through Time



**Figure 11:** Increase in Hospital Admissions by Disease in Different Time Periods

positive/negative externalities in both micro (state) and macro (municipal) levels.

Due to the large Brazilian territorial extension and its generation portfolio, this type of analysis is particularly important since, as the electric grid is integrated, electricity generation and consumption may not occur in the same region, meaning that the potential pollution burden may not be balanced with local economic development. The model provides a spatial vision of the entire process, allowing results to be analyzed in an aggregated way (economic, environmental and public health total impact) or disaggregated by region, determining more sensitive locations to pollution problems and/or economic benefits.

The importance of temporal and spatial dimensions in impact analysis could be evidenced in the case study performed for the Osório Wind farm. Although larger economic impacts and pollution were estimated for the RS scenario, economic spillovers and emissions were less spread than other construction sites. On the contrary, although the CE scenario presented smaller total economic output, it had a larger capacity for jobs creation but a wider spatial scope of negative externalities that translated into higher public health impacts. Regional idiosyncrasies regarding local eco-

conomic structure, interregional multipliers, emission coefficients and health care infrastructure were essential to perform this more accurate assessment than traditional I-O models. EPSIM software was able to properly address the transient demand from electrical investments and to provide economic, environmental and public health effects in spatio-temporal dimensions for comparisons between different scenarios.

Nevertheless, some limitations in the proposed model must be highlighted: as discussed above, the I-O framework is not suitable for long-run forecasts once the economy's structure changes through time. Thus, the use of dynamic computable general equilibrium or econometric I-O models are alternatives to better assess economic impacts; the simple GPM presented can be enhanced by adding extensions for airborne chemical reactions; and better databases regarding industrial location, morbidity rates and health care infrastructure in municipal level may increase the estimations' accuracy.

In sum, planners can benefit from our model by exploring the impacts of diverse energy sources and locations, assessing economic, environmental and social aspects of each alternative. Electricity will still remain as an essential input in the future as well as its environmental concerns. Sustainability is a challenge to be addressed today for a long-term benefit. The more tools society can rely on, better decisions can be made and a cleaner future planned.

## 6 Acknowledgments

The authors wish to thank Professor Dorel Soares Ramos from POLI/USP for comments and materials on the Brazilian electrical grid. This work was partially developed under CAPES/FIPSE Exchange Program "Global Talent Development for Sustainable Agricultural & Environment Sciences Fields" with financial support from CAPES.

## 7 References

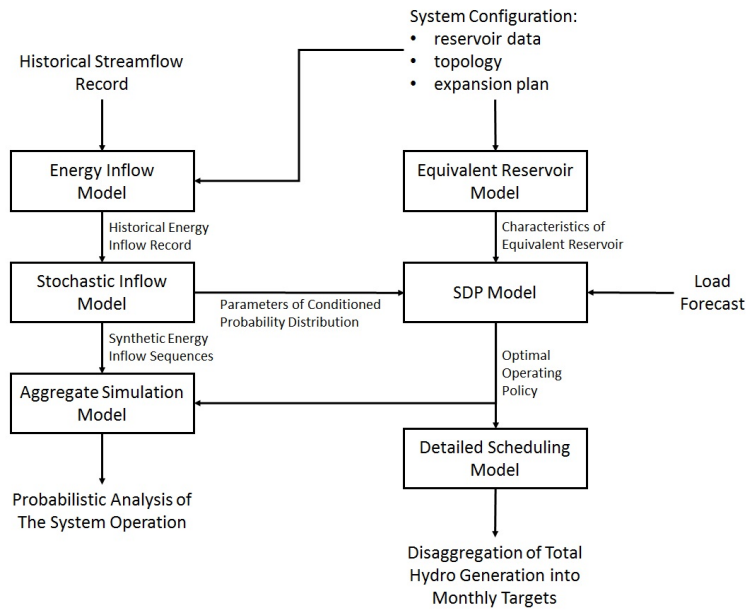
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## A The Operations Planning Model



Source: ENGENCORPS (1998c).

## B Sectorial Classification According to Production Mode

<b>Sector</b>	<b>Production Mode</b>
Agriculture	Anticipatory
Mining	Anticipatory
Iron and Steel Industry	Anticipatory
Chemical Industry	Anticipatory
Cement Manufacturing	Anticipatory
Nonferrous Metal Metallurgy (mainly aluminum)	Anticipatory
Other Industries	Responsive
Electric Power Sector	Responsive
Air Transportation	Responsive
Truck Transportation	Responsive
Transportation – Others	Responsive
Other Sectors	Responsive

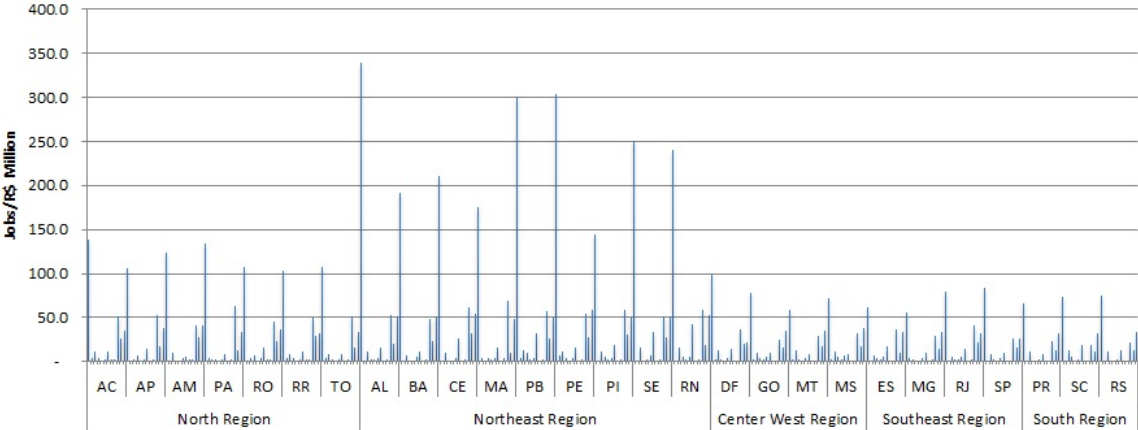


## C Estimated Cost Structure for the Osório Wind Farm (2004)

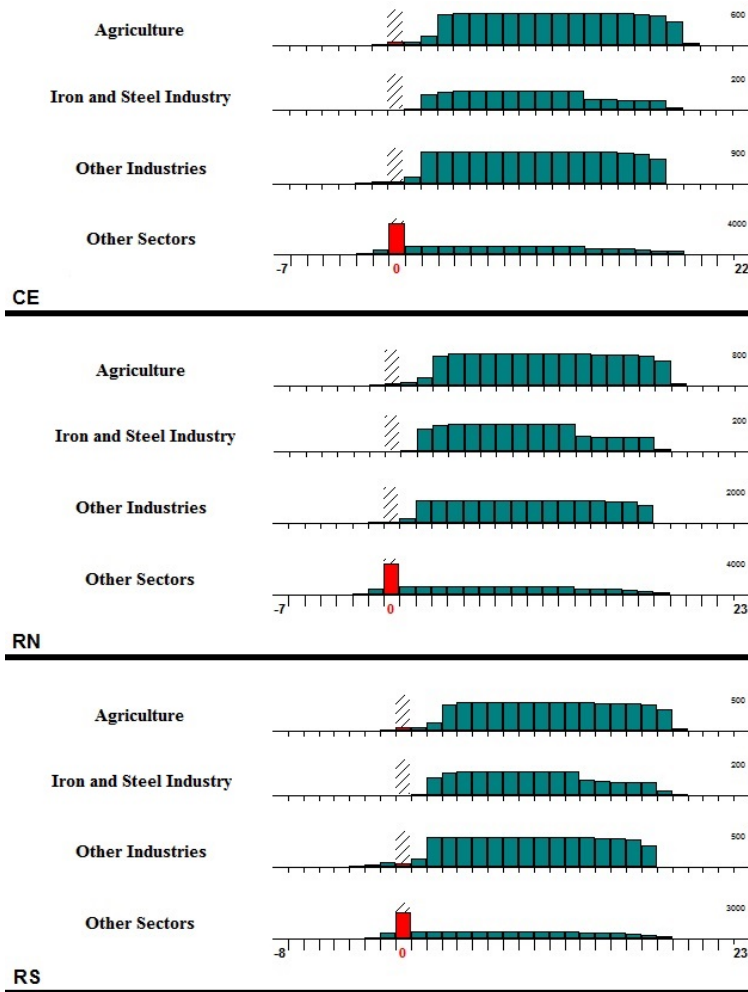
	Expenses %	R\$
<b>Construction</b>	22%	
Concrete		R\$ 12,222,214.09
Steel		R\$ 11,151,818.18
Iron		R\$ 11,151,818.18
Civil Construction		R\$ 112,874,149.55
		<b>R\$ 147,400,000.00</b>
<b>Towers</b>	10%	
Concrete		R\$ 19,223,288.18
Steel		R\$ 47,776,711.82
		<b>R\$ 67,000,000.00</b>
<b>Interest Paid During Construction</b>	4%	<b>R\$ 26,800,000.00</b>
<b>High Voltage Substation/Interconnection</b>	4%	<b>R\$ 26,800,000.00</b>
<b>Development Activities</b>	4%	<b>R\$ 26,800,000.00</b>
<b>Financing and Legal Taxes</b>	3%	<b>R\$ 20,100,000.00</b>
<b>Project and Engineering</b>	2%	<b>R\$ 13,400,000.00</b>
<b>Terrestrial Transportation</b>	2%	<b>R\$ 13,400,000.00</b>
<b>Turbines</b>	49%	<b>R\$ 328,300,000.00</b>
<b>Total</b>	100%	<b>R\$ 670,000,000.00</b>

Sources: Adapted from Ventos do Sul Energia (2007) and Windrock International (2004).

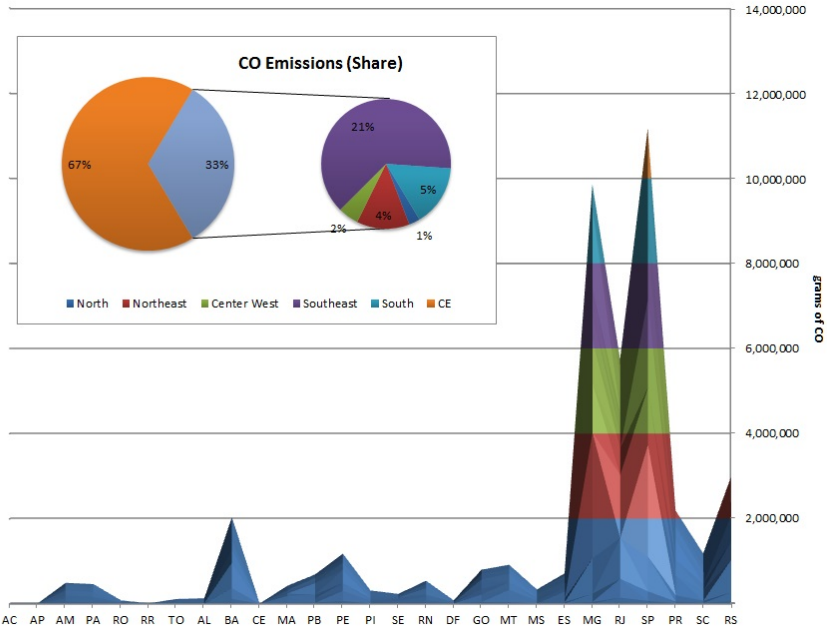
### D Employment Coefficients by State



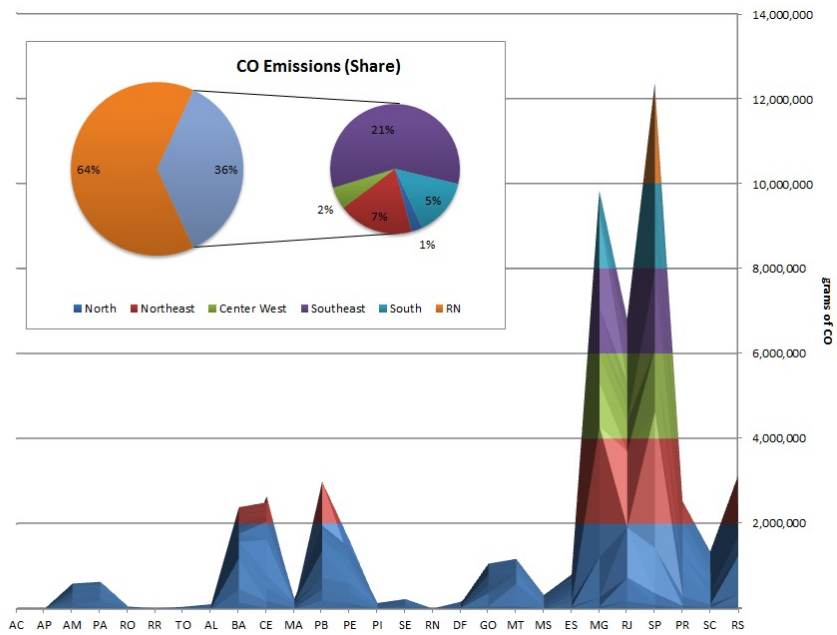
## E Employment Dynamics Through Time, Main Sectors



**F CO Emissions by State and Total Share, CE (CE emissions removed)**



G CO Emissions by State and Total Share, RN (RN emissions removed)



H CO Emissions by State and Total Share, RS (RS emissions removed)

