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EPSIM - 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. This study proposes a social-environmental economic model, based on Regional Sequential Interindustry Model (SIM) integrated with geoprocessing data, in order to identify economic, pollution and public health impacts in state and municipality levels for energy planning analysis. Integrating I-O framework with electrical and dispersion models, dose-response functions and GIS data, this model aims to expand policy makers' scope of analysis and provide an auxiliary tool to assess energy planning scenarios in Brazil both dynamically and spatially. Moreover, a case study for wind power plants in Brazil is performed to illustrate its usage.

1. Introduction

The electrical sector is responsible for a considerable amount of greenhouse gases emissions worldwide, but also the one in which modern society depends the most for maintenance of quality of life as well as the functioning of economic and social activities. The Kyoto Protocol and IPCC (Intergovernmental Panel on Climate Change) reports on climate change identify sustainable development and rational resources use as key points to future. Thus, energy planning should consider not only economic impacts, but also environmental and social effects during the entire investment life cycle and idiosyncrasies of the chosen location.

Brazilian energy matrix is one of the least polluting in the world, especially due to its domestic electricity supply, which has low pollutant emission indexes since it is concentrated in renewable energy sources (91.5%). Nevertheless, the generation portfolio is not too diversified with predominant supply of hydropower plants (81.7%) and low shares of other "clean" sources such as biomass (6.5%), nuclear (2.7%) and wind (0.5%), which increase energy security issues (MME 2012).

Since 2003 an electricity consumption rebound has raised per capita growth rates to 5% annually in Brazil (Tolmasquim 2005). During all this phase, income elasticity measures for electricity consumption were superior to the unit, which has reflected in a consumption expansion higher than annual GDP growth and an increasing demand for generation infra-structure. In order to comply with this new scenario, several projects have been undertaken in the last years, particularly new wind, gas-fired and thermonuclear plants (ANÁLISE 2010).

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

Several epidemiological studies have confirmed 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 due to the location of emission sources, microclimate dynamic, topography, weather and other factors, confirming the importance of a spatial analysis. Moreover, it is important to notice that pollutants emissions and climate changes 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 (COPPE 2008).

In sum, the recent scenario leads to new discussions about electricity generation portfolios that must be expanded and diversified under the premises of environmental sustainability. Due to these new parameters, different power plants must be assessed not only financially, but also socio-environmentally, considering regional idiosyncrasies, as this study intends. The proposed model allows assessing externalities in different regions and advantages/disadvantages of different sites for a power plant’s project. It is composed by a set of Regional Input-Output matrixes for Brazil and three other modules integrated computationally: Environmental Module, Energy Module and Health Module.

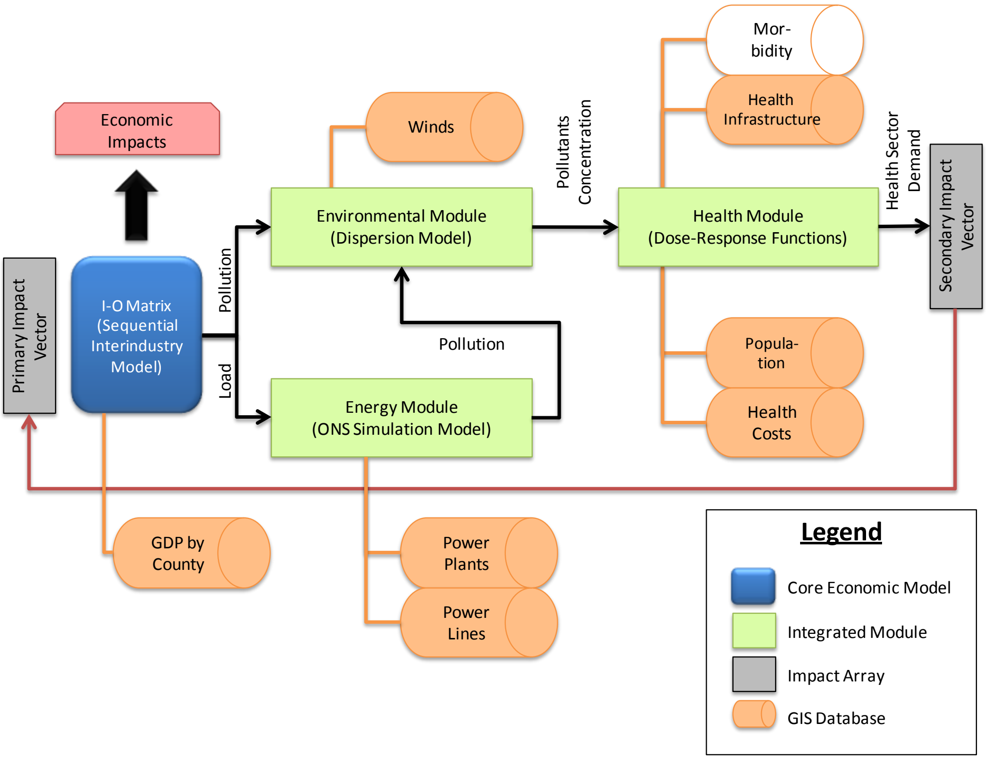
In the next section we describe the proposed model, discussing each module separately. Section three explores the databases used and a case study for Osorio Wind Farm is presented and analyzed in section four. Conclusions follow on section five.

2. Methodology

2.1. Overview

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

Figure 1. General Vision of the Model



The primary characteristic of large construction projects is their transient nature (Romanoff and Levine 1980), i.e., economic impulses (demands) are heterogeneous through time. Their construction, in particular power plants, extends throughout several years before completion. Hence, these projects should not be addressed by static models, which compromise the accuracy of the analysis. The comparison of an equilibrium state before construction and the new equilibrium after construction neglects the existing dynamic in-between these two time periods. Construction is a complex sequential operation which demands different industrial and non-industrial inputs in subsequent phases. As each project has a unique cost, location and technology, distinct evaluations must be performed for each project individually and impact analysis is not transferable to other projects.

The proposed model is divided into four interconnected components – (1) Core Economic Model; (2) Environmental Module; (3) Energy Module; and (4) Health Module – with a feedback system in the end of the process to iterate the algorithm. The model is computationally built and it allows assessing benefits and downsides of different 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 of the construction phase of the power plant are estimated for each region. The advantage of using a SIM is being able to analyze how irregular demand flows in different stages of construction dynamically impact the economy over several time periods. Then, once pollution coefficients are determined for each industry type, it is possible to estimate total pollution generated by the economy and the location of these emissions. Total pollution has, thus, two dimensions: physical units of pollutants and its source location. These variables are inputs to the Environmental Module which assesses the dispersion of pollutants and forecasts their concentration in each municipality.

The required industrial output for the construction also raises the demand for electricity, which must be supplied with extra generation. The Energy Module emulates the grid operator's (ONS) wheeling system (based on NEWAVE methodology) and is applied to determine which power plants will be dispatched and consequent emissions by location. These outputs are also inputs for the Environmental Module. Finally, pollutants concentrations by location are applied in the Health Module that estimates the demand for health services/products in different regions. This demand is a new shock vector for the Input-Output matrixes that enters the process in an iterative fashion.

Geoprocessing information is used in several databases, providing details about population, wind speed, public health services, etc. for each location. A spatial 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.

2.2. Economic Module

Input-Output (I-O) models allow a detail vision of both macroeconomic and microeconomic impact of policy effects in a certain region, through the analysis of industrial interdependency within an economy. The production of a good or service has two consumption destinations: either be 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:

$$X_i = z_{i1} + z_{i2} + \cdots + z_{ii} + \cdots + z_{in} + Y_i \tag{1}$$

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 certain 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). It is supposed constant according to the premise of constant returns of scale (Miller and Blair 2009).

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{X}}^{-1} \tag{2}$$

Fixed technical coefficients imply 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 (Labandeira and Labeaga 2002). Replacing (2) in (1), rearranging in matrix form and solving the equations to determinate total output required to final demand ($\mathbf{Y}$):

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

$(\mathbf{I} - \mathbf{A})^{-1}$ is Leontief Inverse, 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.

The Sequential Interindustrial Model (SIM) is built on the static I-O model with the insertion of a time framework in industrial processes. SIM is based on time-phased production, i.e., production process occurs sequentially in time, differently from the static I-O model which assumes that production occurs simultaneously during a single time-step. This 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).

Two hypotheses must be made for the time interval *t*: it is equal for all industries and constant through time; and 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 traditional I-O framework. Recalling the fundamental relation expressed in (1) and assuming that time is partitioned into discrete industry intervals, during the t^{th} interval the I-O model can be rewritten as:

$$\mathbf{X}_{\mathrm{t}} = \mathbf{Z}_{\mathrm{t}} + \mathbf{Y}_{\mathrm{t}} \tag{4}$$

The next step would be determining the coefficient matrix **A** for the economy. Nevertheless, as two production process with distinguish dynamics coexist, responsive and anticipatory industries will differ in relation to time steps required. In the responsive model, the intermediate yield is expressed as:

$$\mathbf{Z}_{\mathrm{t}} = \mathbf{A}\mathbf{X}_{\mathrm{t-1}} \tag{5}$$

Meaning that intermediate yield at interval *t* is linked to total supply at interval *t–1*. On the contrary, in the anticipatory model, intermediate yield at interval *t* is supposed to be linked to total supply at interval *t+1*, resulting in:

$$\mathbf{Z}_{\mathrm{t}} = \mathbf{A}\mathbf{X}_{\mathrm{t+1}} \tag{6}$$

The responsive model is derived by replacing (5) into (4) and the anticipatory model by replacing (6) into (4). Finally, using the double-sided Z transform one derives de pure responsive model and the pure anticipatory model, respectively:

$$\mathbf{X}_{\mathrm{t}} = \sum_{\mathrm{r}=0}^{\infty} \mathbf{A}^{\mathrm{r}}\mathbf{Y}_{\mathrm{t-r}} \tag{7}$$

$$\mathbf{X}_{\mathrm{t}} = \sum_{\mathrm{r}=0}^{\infty} \mathbf{A}^{\mathrm{r}}\mathbf{Y}_{\mathrm{t+r}} \tag{8}$$

However, as the economic structure is composed of both anticipatory and responsive industries, one needs to define a mixed model which comprises the two production processes. This system may be formalized as:

$$\mathbf{X}_{\mathrm{t}} = \mathbf{A}_1\mathbf{X}_{\mathrm{t+1}} + \mathbf{A}_2\mathbf{X}_{\mathrm{t-1}} + \mathbf{Y}_{\mathrm{k}} \tag{9}$$

Hence, the solution takes the form:

$$\mathbf{X}_{\mathrm{t}} = \sum_{\mathrm{r}=-\infty}^{\infty} \mathrm{G}_{\mathrm{r}}(\mathrm{A}_1, \mathrm{A}_2)\mathbf{Y}_{\mathrm{t-r}} \tag{10}$$

Where $G_r(A_1,A_2)$ is a matrix function that has all path gains by industries until time period *t*. This single region model may also be translated into an interregional model if one considers the matrixes in (9) as compositions of regional matrixes. Hence, for a two regions (L and M) example:

$$\begin{bmatrix} \mathbf{X}_{\mathrm{t}}^{\mathrm{L}} \\ \mathbf{X}_{\mathrm{t}}^{\mathrm{M}} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_1^{\mathrm{LL}} & \mathbf{A}_1^{\mathrm{LM}} \\ \mathbf{A}_1^{\mathrm{ML}} & \mathbf{A}_1^{\mathrm{MM}} \end{bmatrix} \begin{bmatrix} \mathbf{X}_{\mathrm{t+1}}^{\mathrm{L}} \\ \mathbf{X}_{\mathrm{t+1}}^{\mathrm{M}} \end{bmatrix} + \begin{bmatrix} \mathbf{A}_2^{\mathrm{LL}} & \mathbf{A}_2^{\mathrm{LM}} \\ \mathbf{A}_2^{\mathrm{ML}} & \mathbf{A}_2^{\mathrm{MM}} \end{bmatrix} \begin{bmatrix} \mathbf{X}_{\mathrm{t-1}}^{\mathrm{L}} \\ \mathbf{X}_{\mathrm{t-1}}^{\mathrm{M}} \end{bmatrix} + \begin{bmatrix} \mathbf{Y}_{\mathrm{t}}^{\mathrm{L}} \\ \mathbf{Y}_{\mathrm{t}}^{\mathrm{M}} \end{bmatrix} \tag{11}$$

The only difference between pure systems and the mixed one is the production chronology. The production output of the former models is equal to the mixed production model, and also equal to that of the static I-O model.

In order to analyze the interface within industrial dynamic, pollutants emissions and additional electricity load, two extensions are required. Considering only two regions L and M, firstly, a pollution intensity (**p**) vector, which measures the amount of pollution emitted by industries in each region (tons of pollutant / R$ Million), is determined for each industry:

$$\mathbf{p}^{\mathrm{L}} = \widehat{\mathbf{X}^{\mathrm{L}}}^{-1}\mathbf{TP}^{\mathrm{L}} \tag{12}$$

Where TP^{L} is a nx1 vector comprising total emissions discharged in one year for each industry in region L. One must note that the electricity sector does not have a coefficient, once it will be estimated separately, using the Energy Module, avoiding double counting. Secondly, 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 *i* at region L:

$$\mathbf{e}^{\mathrm{L}} = \widehat{\mathbf{X}^{\mathrm{L}}}^{-1}\mathbf{CTE}^{\mathrm{L}} \tag{13}$$

Where $\mathrm{CTE}^{\mathrm{L}}$ is a nx1 vector with total electrical consumption in one year for each industry in region L. Thus, energy intensity is measured by total energy requirement divided by total production value, not just added value.

Finally, the model makes two estimation steps: first, it calculates total production ($\dot{\mathbf{X}}$) – comprising direct, indirect and induced effects – from the power plant construction demand ($\dot{\mathbf{Y}}$) using SIM. These values are converted into emissions in order to determine total pollutants released during implantation ($\dot{\mathrm{P}}_{\mathrm{c}}$). The $\dot{\mathbf{P}}_{\mathrm{c}}$ vector contains pollution released by each industry in each region. It is the output of the economic model to the Environmental Module (pollution by location). Second, it estimates the electricity load for the construction ($\dot{\mathbf{E}}_{\mathrm{c}}$) by postmultiplying the diagonalized total production ($\dot{\mathbf{X}}$) by the energy intensity vector (**e**). This vector contains electricity requirements by industry in each region and is the output of the economic model to the Energy Module (electricity by location). These vectors also have a time dimension from the SIM model.

2.3. Energy Module

The Energy Module simulates the grid wheeling operation, which must maintain a static and a dynamic equilibria in order to keep the system's integrity. The basic operational idea for the grid administration is to minimize the energy price to consumers, subject to the transmission lines constrains. The concept is that inflexible power plants (hydropower, nuclear, wind and some thermal) are always connected to the grid and, thus, if there is an extra load in the system, they are preferred to increase generation to attend this demand.

In Brazil there is an Independent System Operator called National System Operator (ONS) responsible for coordinate the dispatch of the hydrothermal system on a tight poll basis with published prices for thermal plants and central dispatch for hydro plants. The objective of ONS is to provide an efficient (minimizing fuel costs in thermal plants) and reliable (avoiding supply interruptions and rationing) supply of electricity to consumers in the entire planning period.

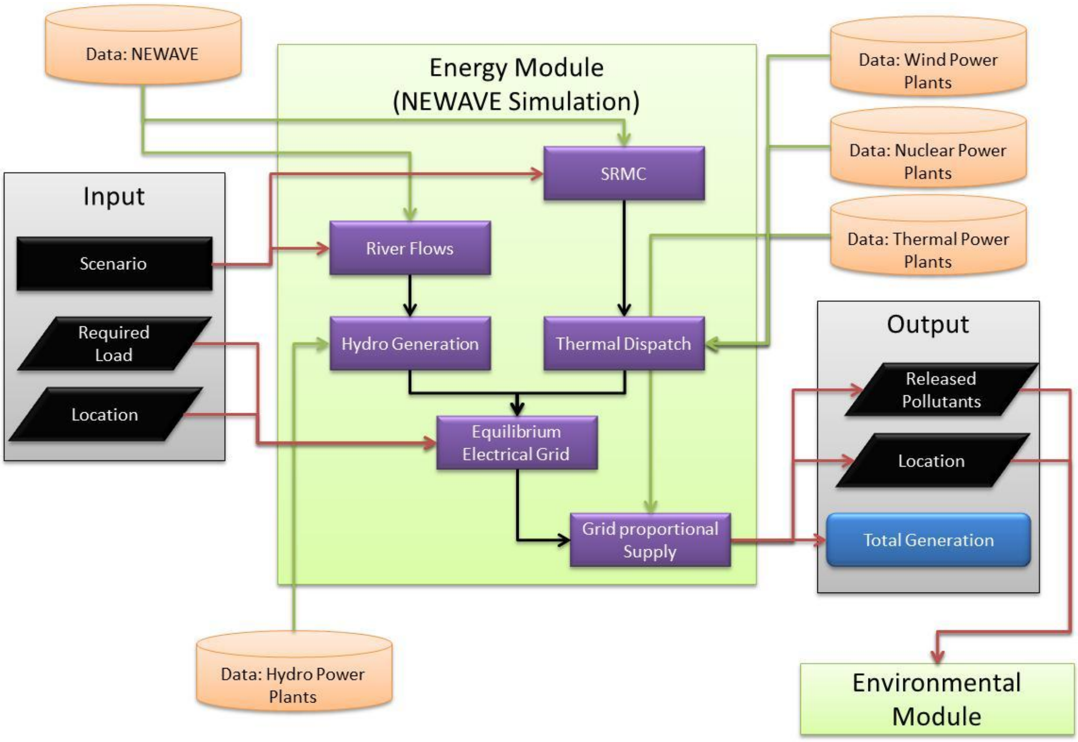
In pure thermal systems, the generation dispatch problem is to minimize costs (fuel basically) subject to the static equilibrium of the grid and capacity restrictions (also observing factors as losses, transmission limitations, startup costs, etc.). Hence, power plants are dispatched by increasing operating 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 (Engecorp 1998a).

In hydrothermal systems, reservoirs act as energy storage and are used to reduce fuel costs with thermal generation. Nonetheless, hydrological uncertainty and downstream configuration of plants, i.e., hydro plants built in a same river stream, pose a much more complex intertemporal problem to optimize. The dispatch problem in this case is to minimize immediate and future operating costs under uncertainty, subject to the same constraints as before plus reservoirs capacities. There is a trade-off between depleting reservoirs in *t* or storing water for future periods, and hence the system operation is coupled in time (Engecorp 1998a). Moreover, differently from pure thermal systems, dispatch and supply availability are intrinsically correlated, since maximize supply reliability is to base-load all thermal units while minimize operational cost is to rely only on hydro plants for power supply (which decreases reliability). The tradeoff factor is, hence, to estipulate either an acceptable risk of deficit or a cost of deficit.

Taking in consideration all these idiosyncrasies of the Brazilian hydrothermal system, the NEWAVE model was conceived (see Appendix 1). Due to hydrological seasonality, diverse micro regional climate and uncertainty associated to atmospheric dynamics, forecasts of the inflows to reservoirs 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. Relying on a historical series of water affluence since 1931, the system operation is simulated for a sample of 2,000 synthetic energy inflow sequences for a 5 years horizon and a target energy shortage risk of 5% per year (ENGERCORP 1998c). Then the system short-run marginal cost (SRMC) per month 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 (ENGERCORP 1998b).

NEWAVE is a well-established model used since 1979 by the coordination pool in Brazil and due to the complexities and large volume of not publically available data used it will not be reproduced in our model. The algorithm (Fig. 2), however, utilizes the output of the model, the SRMC table calculated for 2008, hydro generation and thermal power plants data to simulate the dispatch under different hydrological scenarios.

Figure 2. Energy Module



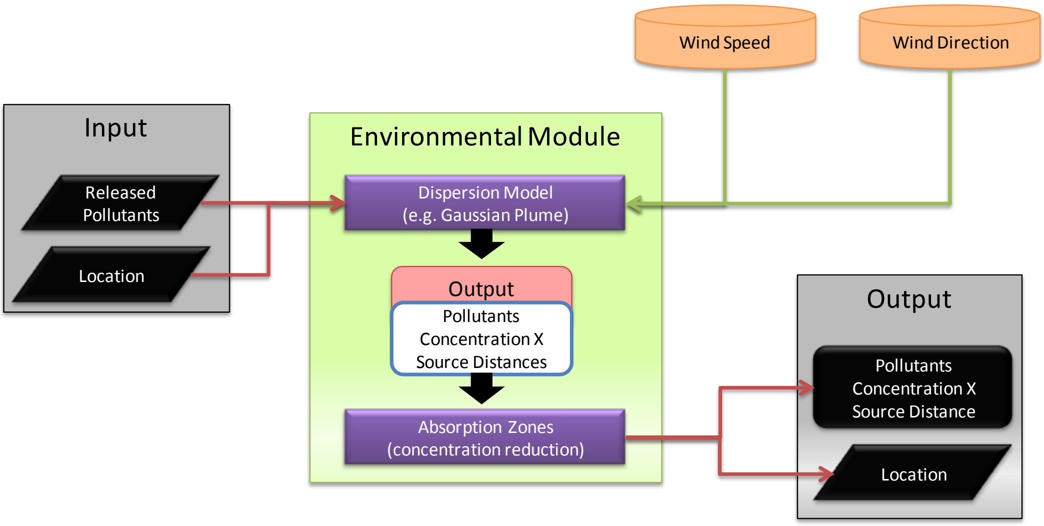
After selecting the scenario year, a water inflow pattern determines the hydro generation and the SMRC is stipulated for each month. From the SMRC, power plants are dispatched according to inflexibility and operational cost, i.e., all plants with cost below the SMRC are dispatched. This determines the steady-state of the system and the generation share of each plant. As the monthly load induced by the industrial output is quite marginal compared to the baseload, we assume that this load is not significant enough to require new thermal dispatches. Therefore the extra required generation can be supply by the currently dispatched plants and it is done proportionally to the share of total generation per plant. Pollution from dispatched thermal plants is estimated and sent to the Environmental Module (total emission, location and time period).

2.4. Environmental Module

Both Economic and Energy modules send their outputs to the Environmental Module containing quantity of pollutants released to the atmosphere, type and the location of the source by time period (Fig. 3). Using GIS data for meteorological conditions, a

Gaussian Plume Model (GPM) is applied for each region to determine the total concentration of pollutants at different distances from the source, considering the effect of one region in another.

Figure 3. Environmental Module



Pollutants are carried by wind and diluted by atmospheric turbulence until final deposition in the ground. Some compounds may react in the atmosphere and form secondary pollutants like H_2SO_4 and O_3. As in this study only primary pollutants are assessed and they are chemically stable close to the emission source, a simple GPM (without any extensions that account for chemical reactions) is used to predict pollutants concentration. The model assumes that continuously released pollutants are carried in a straight line by wind and mix with the air both horizontally and vertically resulting in pollutant concentration with a normal (Gaussian) spatial distribution (European Commission 2005). We consider a homogeneous emission rate throughout the time period and concentration at ground level only. It is formalized as:

$$c(x,y,z) = \frac{Q}{2\pi u \sigma_Z \sigma_y}\left\{exp\left(\frac{-(z-h)^2}{2\sigma_Z^2}\right) + \exp\left(\frac{-(z+h)^2}{2\sigma_Z^2}\right)\right\}\left\{exp\,\frac{-y^2}{2\sigma_y^2}\right\} \qquad (14)$$

Where *c(x,y,z)* is the atmospheric concentration at any point *x* meters downwind of the source, *y* laterally from the centerline of the plume and *z* meters above ground level; *Q*: emission rate; *u*: wind speed; *h*: stack height; σ_y: cross wind standard deviation (measure of plume width); and σ_Z: 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. Through this model one may assess the concentration of pollutants as far as 100 km from the emission source (Salby 1996).

This 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 source at several time periods. This data is used in the Health Module for public health impact evaluation.

2.5. Health Module

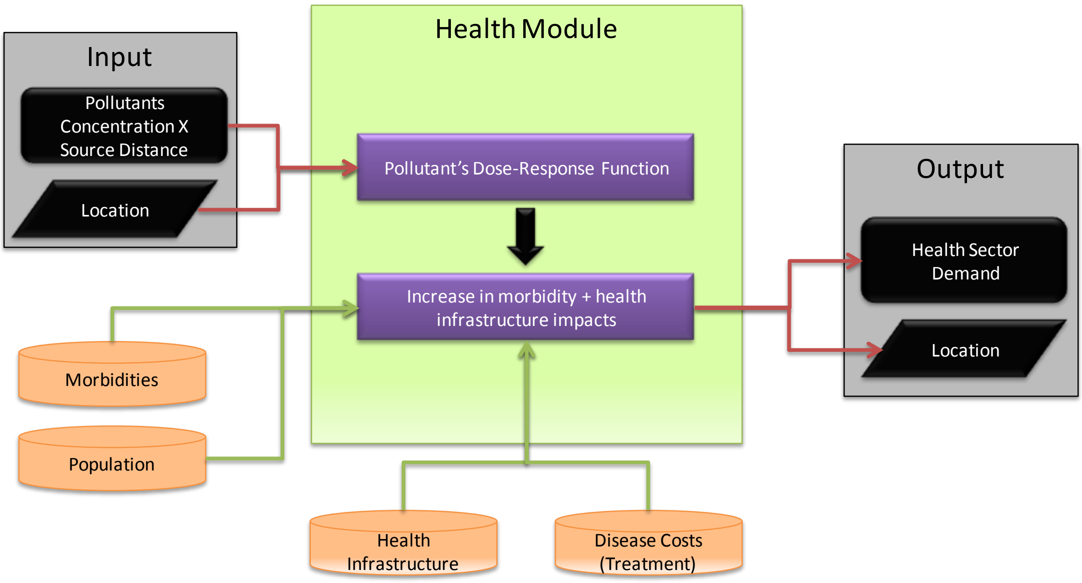
The Health Module receives concentration data, with location and time period, for each pollutant considered in the Environmental Module (Fig. 4). Adding it to preexisting pollution on site at time period t, total pollutants concentration (pc_t) can be estimated by region. Then, deleterious effects are forecasted through dose-response functions (DRF) which calculate 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 an agent is been exposed to the physical impact on this receptor. Following the discussion by Pope (2000), we consider that the DRFs do not have any threshold point. The impacts of NO_2 and SO_2 are assumed to increase indirectly from the particulate nature of nitrate and sulfate aerosols, and CO_2 impact is measured by CO effects (which derives from an inefficient combustion of CO_2).

In order to transform public health effects into demand for health care services, the average cost per patient admitted in public hospitals is considered for each type of disease ($cost^{disease}$), besides the last hospital admission rate by region ($admis_{t-1}$). The final monetization of impacts is accomplished by estimating the number of excess diseases due to the pollution ($admis_{t-1}*DRF(\bullet)$) and multiplying it by the treatment cost for each disease. Hence, for region L, the health sector demand at time t (h_t^L) depends on the current number of hospitalizations, the increase in morbidity cases and the local treatment cost:

$$h_t^L = admis_{t-1}^L * DRF(pc_t^L) * cost^{L,disease} \tag{15}$$

It is important to notice that although the number of cases increases in a certain region, the effective health demand may not occur in this region due to a lack of available health care services. Hence, we consider that population can migrate to nearby regions seeking for 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 Software

The national I-O matrix for Brazil was derived according to the methodology presented in Guilhoto and Sesso Filho (2005a), while the estimation of the interregional I-O system was made following the methodology presented in 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 works more disaggregated data shall be used.

In order to create a mixed SIM, these sectors were classified into responsive and anticipatory production mode. As highlighted by Romanoff and Levine (1986), anticipatory mode is usual in sectors as agriculture, mining and manufacturing industries, in which production typically anticipates orders with readymade standard products. Responsive mode, in 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 Appendix 2. Moreover, the time step *t* is considered monthly intervals.

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 matrixes 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 industry and commerce consumed 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
Siderurgy Industry	245.26
Chemistry Industry	85.80
Cement Manufacturing	597.06
Nonferrous Metal Metallurgy (mainly aluminum)	1,781.01
Other Industries	104.60
Electric Energy 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 details allows a more accurate analysis of pollutants 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_2 levels will be assessed.

For industrial emissions, there is not a database for industries' locations, fact that limits the scope of the analysis. To overcome this issue, based on the economic structure of a state (from the I-O matrix), each municipality within that state is allocated with 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_2 emissions are estimated based on individual coefficients for each industry type, based on MCT (2009) for 2004 pollution. The only sector without emissions is "Electric

Energy Sector" to avoid double counting with the Energy Module. In order to obtain CO and NO_2 levels, based on data for 2004 from ECEN (2010), two additional conversion coefficients were set: 1 ton CO_2 = 0.0128 ton CO; and 1 ton CO_2 = 0.0028 ton NO_2.

Table 2. Power Plants Emissions by Type, Brazil, 2004 (kg/MWh)

Power Plant Type	**CO_2**	**CH_4**	**CO**	**N_2O**	**NO_2**
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).

Moreover, for simplification, the surface in Brazil is considered flat to avoid the need for further appendices to the GPM. GIS information regarding wind speed, bearing and latitude/longitude at municipal level is available in CEPEL (SWEARA 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 most comprehensive available emission data for Brazil covers CO_2, CH_4, N_2O, HFC-23, HFC-134, CF_4, C_2F_6 and CF_6 (MCT 2009). But detailed disaggregation is given to the first three pollutants only. 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.

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 in several cities there is access to private health care services, the majority of the Brazilian population (90%) still relies on public health services. Moreover, as high pollutant industries and power plants 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 approach to the real health costs incurred. DATASUS (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.

Table 3. Increase in Morbidity due to 10 μg/m^3 Raise in NO_2 and CO Concentrations

	NO_2	**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.

The model was programmed in Pascal language using Borland Delphi 5 environment and the final software is entitled EPSIM (Energy Planning Sequential Interindustry Model). The program was built in five different units (four modules and an iteration routine) and operates in both state and municipality levels (27 states and 5560 municipalities). In this initial version (implementation 2.0), it was designed to evaluate impacts for construction phase only.

4. Case Study

4.1. Scenario

This case study is based on Osorio Wind Farm located in Rio Grande do Sul, Brazil. Data for this wind power plant was based on Osorio Wind Park that reached full operation in 2007 with 150 MW installed. For construction phase, the expenses structure was estimated with information on total construction costs (R$ 670 million) and materials from Ventos do Sul Company (2007). They were allocated according to an international expenses average for wind farms (Winrock International 2004) (Appendix 3).

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) – by convention, these states are denoted “primary states”. We assume the same construction demand and time (18 months) in all scenarios starting on January. We ran the model for both 1955 and 1983 hydrological trends (the driest and the wettest conditions respectively). This simple case study was developed to exemplify impact analysis and to address convergence in the model 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).

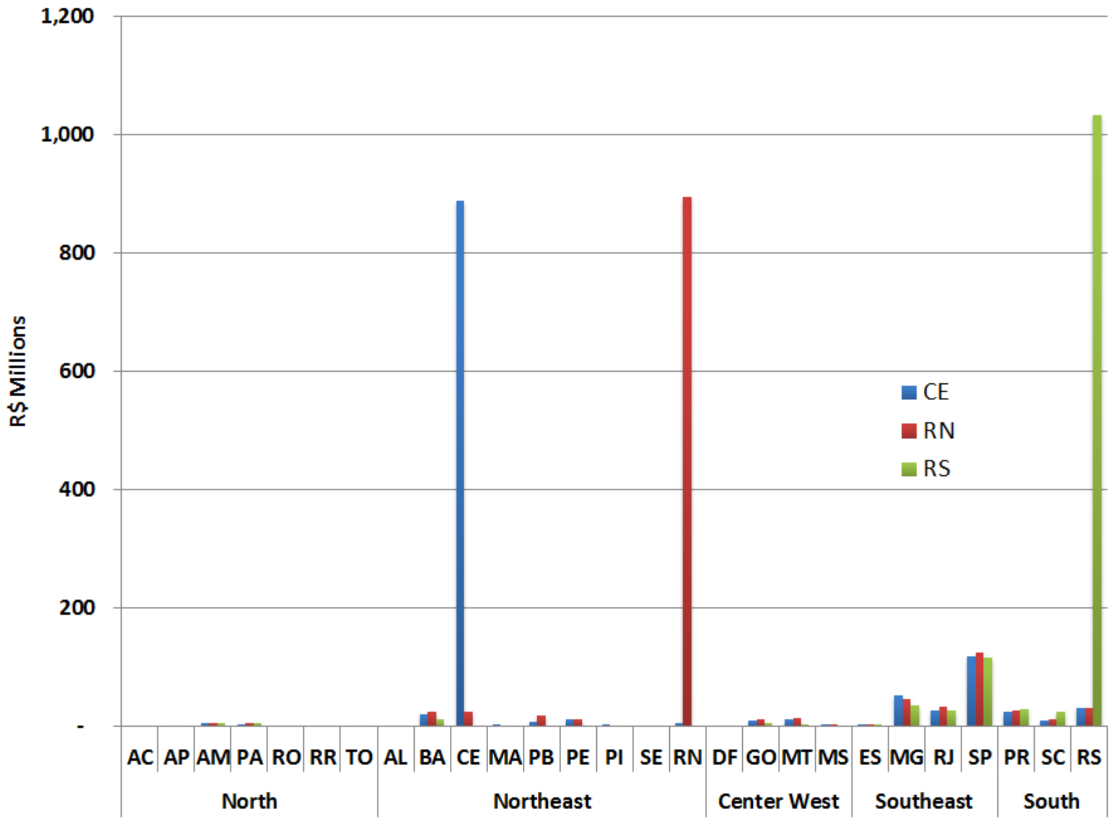
Table 4. Summary of Results for each Scenario

	1955 Scenario			1983 Scenario		
	CE	RN	RS	CE	RN	RS
Economic Impact (R$ Millions)						
Direct	670.00	670.00	670.00	670.00	670.00	670.00
Indirect	588.41	639.76	648.99	588.38	639.73	648.97
Total	**1,258.41**	**1,309.76**	**1,318.99**	**1,258.38**	**1,309.73**	**1,318.97**
Employment						
Total	**41,495**	**51,416**	**27,620**	**41,494**	**51,415**	**27,619**
Electricity Requirements (MWh)						
Total	**142.4**	**149.4**	**153.6**	**142.4**	**149.4**	**153.6**
CO Emissions (Tons)						
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
Total	**1,874.77**	**1,991.10**	**2,036.45**	**1,863.07**	**1,978.84**	**2,023.85**
NOx Emissions (Tons)						
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
Total	**502.72**	**532.76**	**545.43**	**430.29**	**456.75**	**467.27**
Increased Morbidity (Nr cases)						
Ashtma	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
Treatment Cost (R$ Millions)						
Ashtma	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
Total	**4.09**	**2.65**	**3.13**	**4.08**	**2.63**	**3.11**

Total economic impact (direct and indirect) due to the construction was very similar in RS and RN (R$ 1,319 million and R$ 1,310 million respectively), once the overall regional output multipliers in these states are close. However, as RS has larger intraregional and interregional multipliers with 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 with 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 Fig. 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 supply the Northeast region.

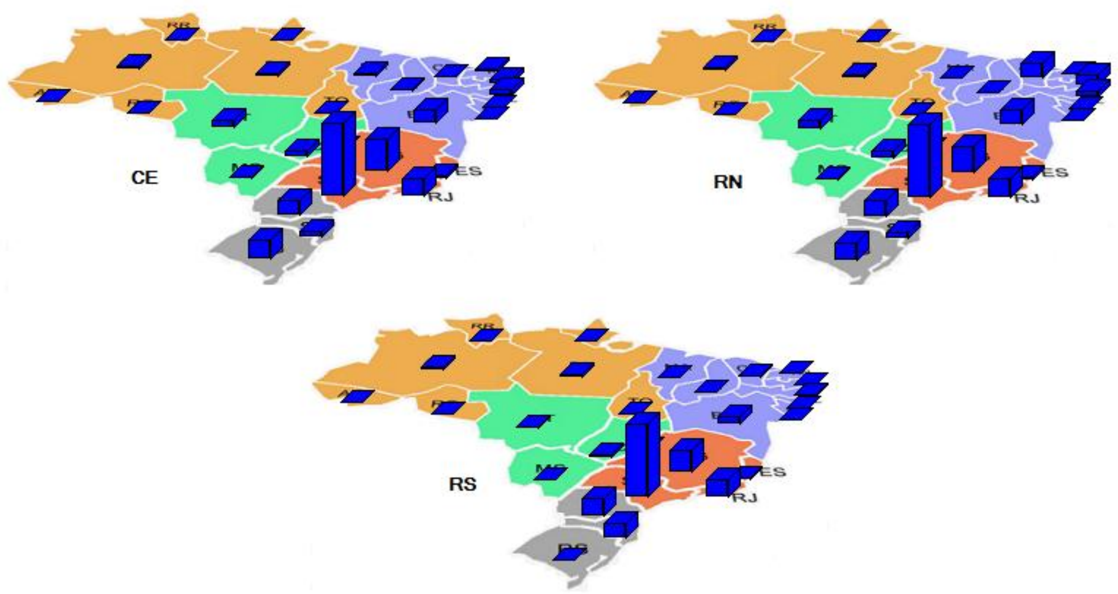
FigURE 5. Total Economic Impact by State (RS, CE and RN scenarios)



Moreover, results also corroborate with the fact that the states of SP, MG and RJ are the most important suppliers to 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.

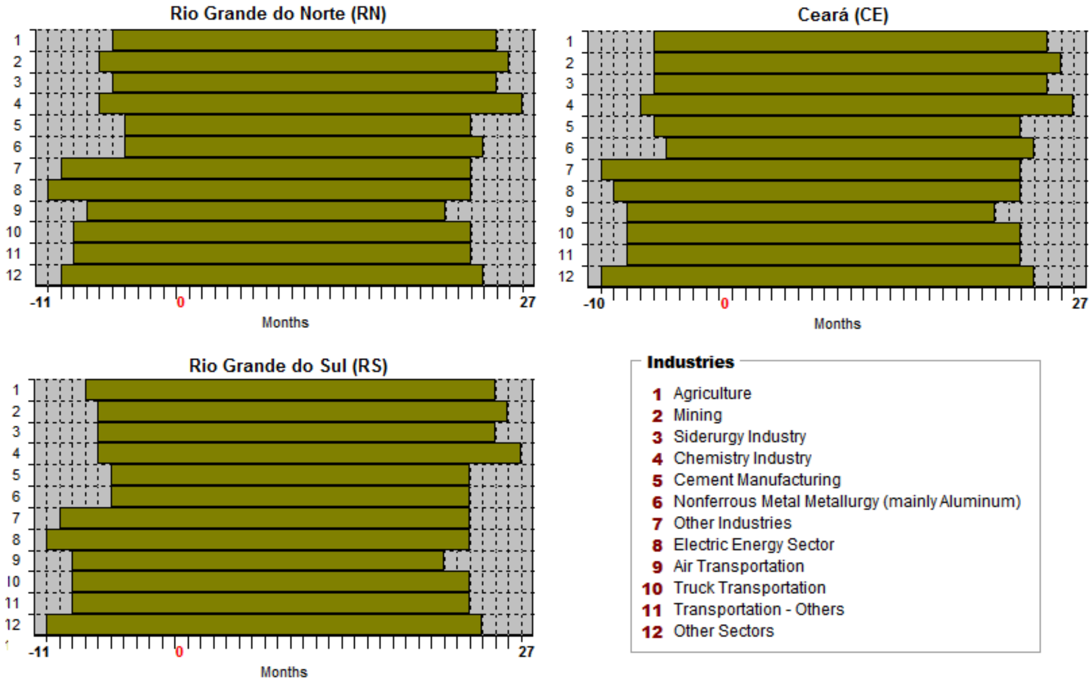
Direct and indirect jobs created also reflect the scope of economic spillovers. They are higher for CE and RN in comparison to RS scenario due to regional idiosyncrasies regarding labor intensity between Northeast and South/Southeast states. Despite the fact that hub states in Southeast region are impacted in all three scenarios, as CE and RN impact significantly several Northeast states and employment coefficients are higher in this region (Appendix 4) due to a labor intensive economic structure, total employment is much higher than in RS case, which impacts mainly capital intensive states. Moreover, most jobs are created during the construction interval and “Agriculture”, “Siderurgy Industry”, “Other Industries” and “Other Sectors” concentrate employment generation in all three scenarios (Appendix 5).

Figure 6. Scope of Economic Spillovers for each Scenario



Obs.: The height of the bars represents the share of impact in the state in relation to total economic impact minus effects on primary state (CE, RN or RS).

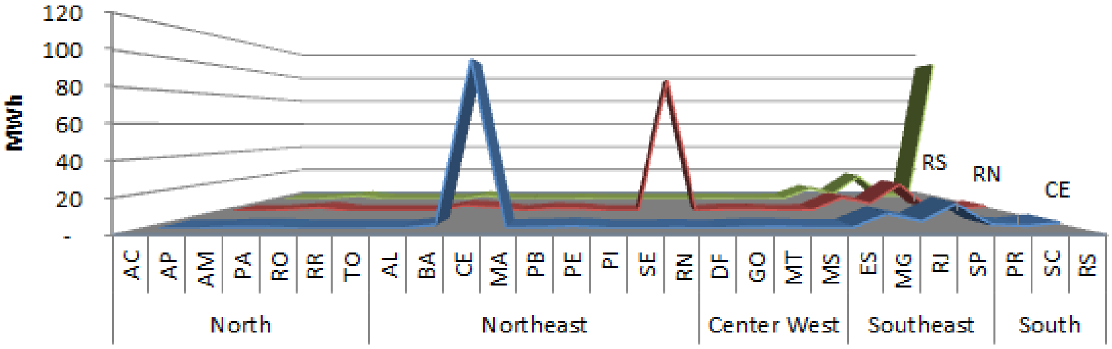
Figure 7. Industrial Activation through Time



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), once the construction demand in months zero and one is strictly related to engineering consulting services and expenses prior to construction (Fig. 7). On subsequent time periods, "Mining", "Siderurgy 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 in 153.6 MWh for RS scenario, 149.4 MWh for RN scenario, 142.4 MWh for CE scenario. Energy requirements pattern is directly related to industrial activation due to economic impacts in each state, as can be noticed by comparing Fig. 5 and Fig. 8. These electricity requirements are compatible with ONS database, representing less than 1% of total electricity consumption in 2004.

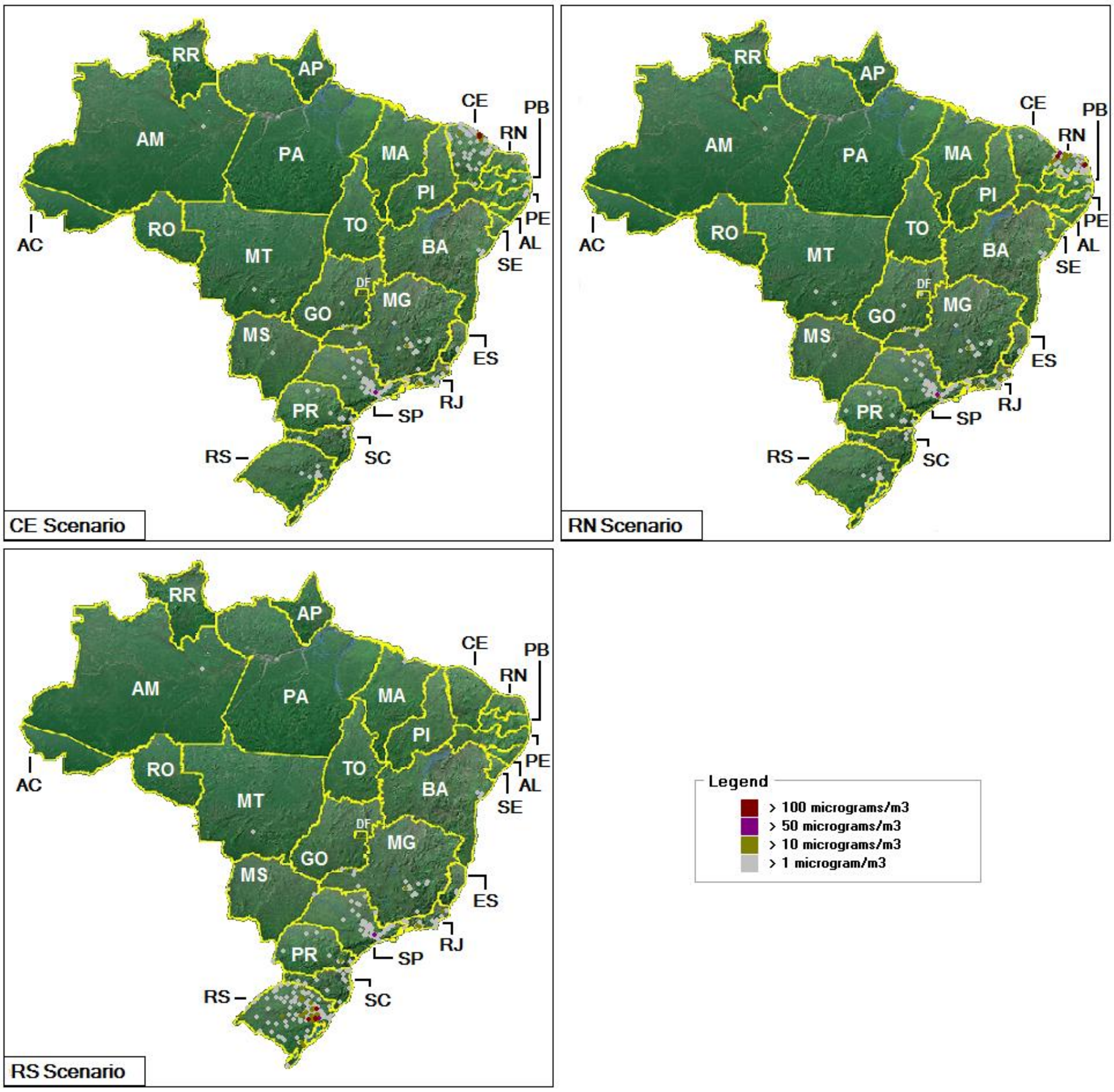
Figure 8. Energy Requirements by State



Total CO and NO_2 emissions can be seen in Table 4 and are also related to total economic impact and energy requirements. Interesting to notice that although part of the emissions are concentrated in the primary state it is also spread to other regions, particularly Southeast states. For CE and RN scenarios, this external negative externality has a particular pattern creating some effects in neighboring states but most of it is concentrated in the Southeast region, causing high pollutants concentrations in SP, MG and RJ (Fig. 9). RS emissions also exhibit this effect, however, RS internalizes more industrial emissions (74.8% of CO emissions) and spreads more negative externalities to neighboring states than distant states (Appendix 6, 7 and 8). NO_2 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, increase in morbidity and total health costs are larger in the former due to the spatial scope of pollutants concentration. Firstly, 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 the increase in hospital admissions occurs in CE resulting in higher treatment costs.

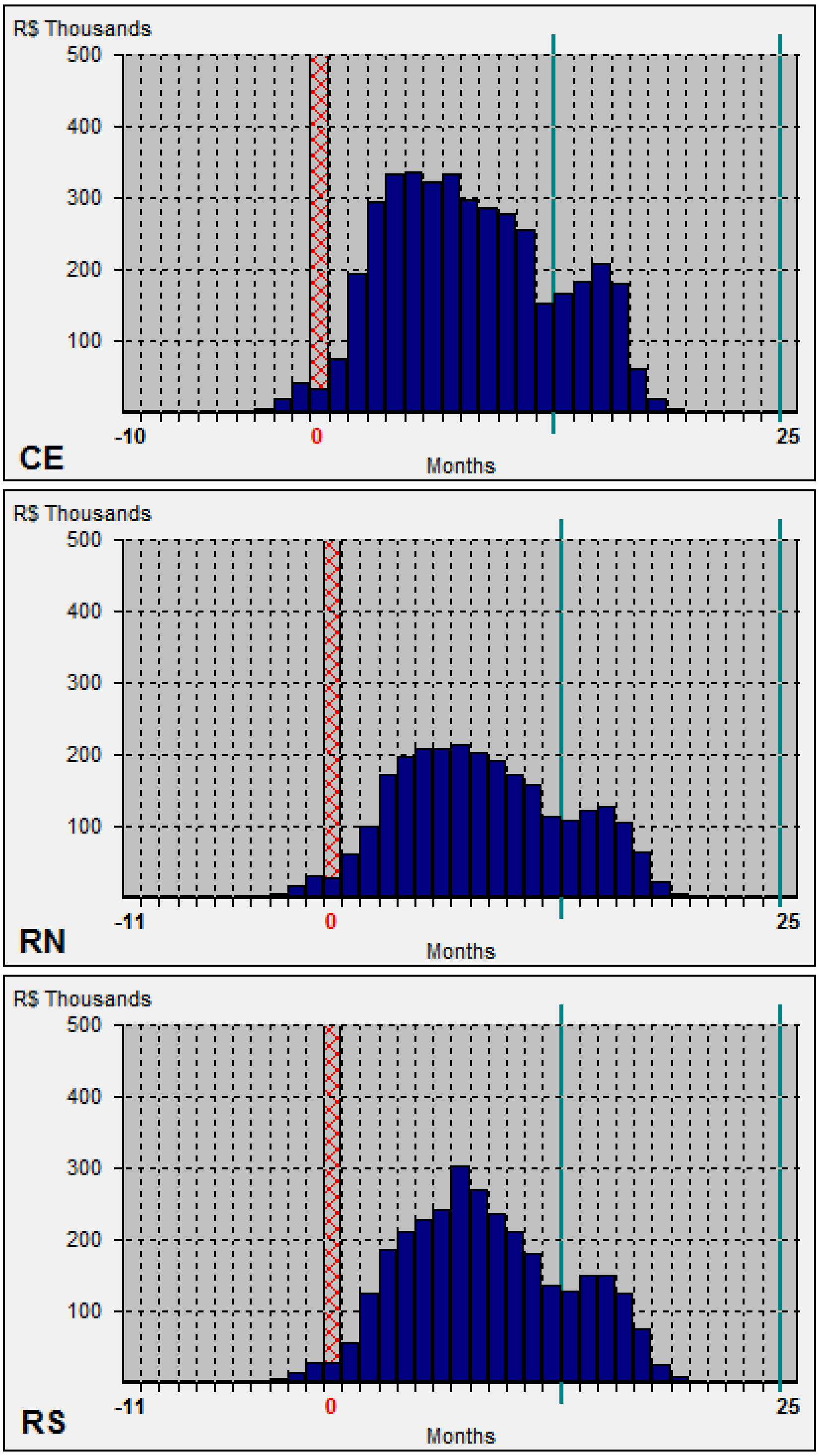
Figure 9. Total CO concentration by state



Secondly, as can be notice in Appendix 6, 7 and 8, CE and RN have large emission scopes which comprise 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 elevated morbidity rates and treatment costs in the Northeast –, while RN affects predominantly other Northeastern states with cheaper treatment costs. On the contrary, 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.

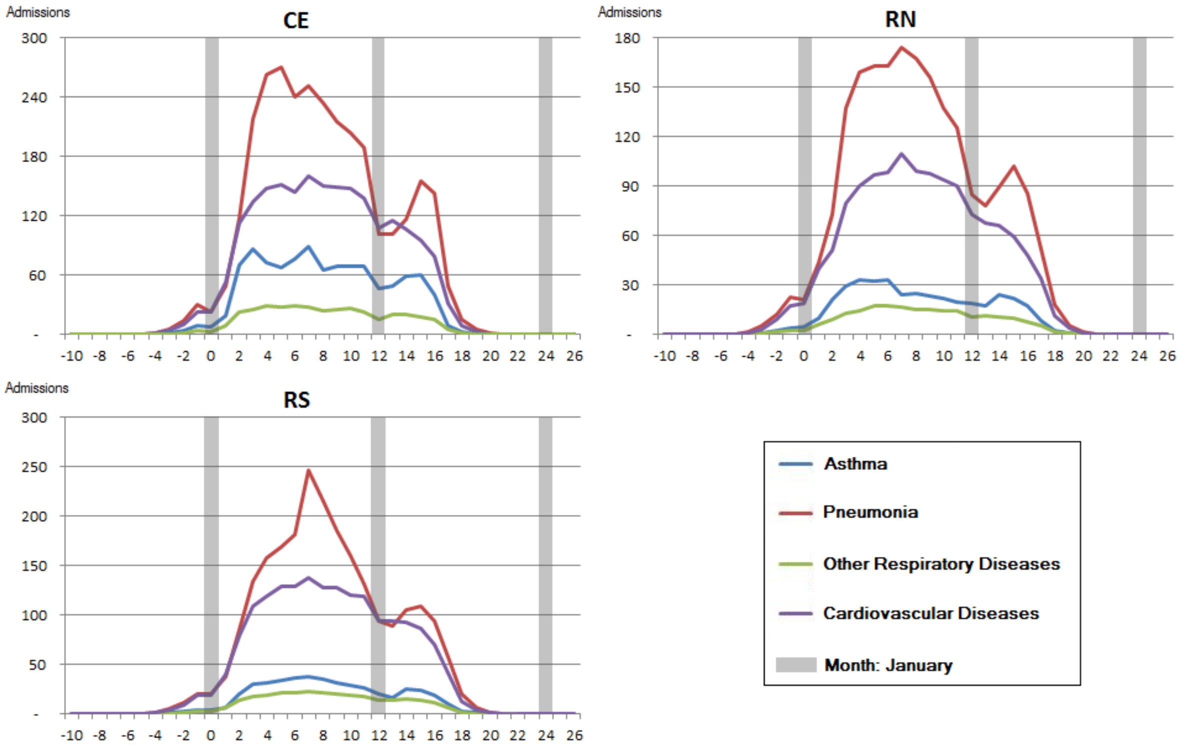
One may also notice that there are important differences in which time period windows health care resources must be mobilized to supply its demand. For RS there is a defined peak in health costs in period 7 and another in period 14, while CE and RN concentrate expenses during periods 4-7 and exhibit a peak in period 15 (Fig. 10).

Figure 10. Health Care Demand through Time



Finally, it is important to highlight the differences in disease prevalence in distinct time periods for each scenario (Fig. 11). As can be noticed, 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 distinctly in time and in each scenario.

Figure 11. Increase in Hospital Admissions by Disease in Different Time Periods



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 proper evaluate its externalities, models coupled with spatial components shall be used. In this study, a hybrid top-down/bottom-up model is proposed, coupling a regional economic model with GIS data and electric-social-environmental specifications. For each power plant site, it estimates total economic impacts, effects on the wheeling dynamic of the electric grid and public health impacts due to pollutants dispersion. Through this model, several locations for the construction of a new power plant can be compared regarding positive/negative externalities in the micro-region (state level) and macro-region (municipal level).

Due to the large Brazilian territorial extension and its generation portfolio, this type of analysis is particularly important once, 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 Osorio Wind farm. Although larger economic impacts and pollution were estimated for RS scenario, economic spillovers and emissions were less spread than other construction sites. On the contrary, although CE scenario presented smaller total economic output, it had a larger capacity of jobs creation but a wider spatial scope of negative externalities which translated into higher public health impacts. Regional idiosyncrasies regarding local economic 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 proper address the transient demand from electrical investments and to provide economic, environmental and public health effects in spatial and temporal dimensions for comparisons between different scenarios.

Nevertheless, some limitations in the proposed model must be highlighted: as discussed above, I-O framework is not suitable for long-run forecasts once the economy' structure changes through time. Thus, considering using a computable general equilibrium (CGE) model is an alternative 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 shall increase estimations’ accuracy.

In sum, planners can benefit from this model 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

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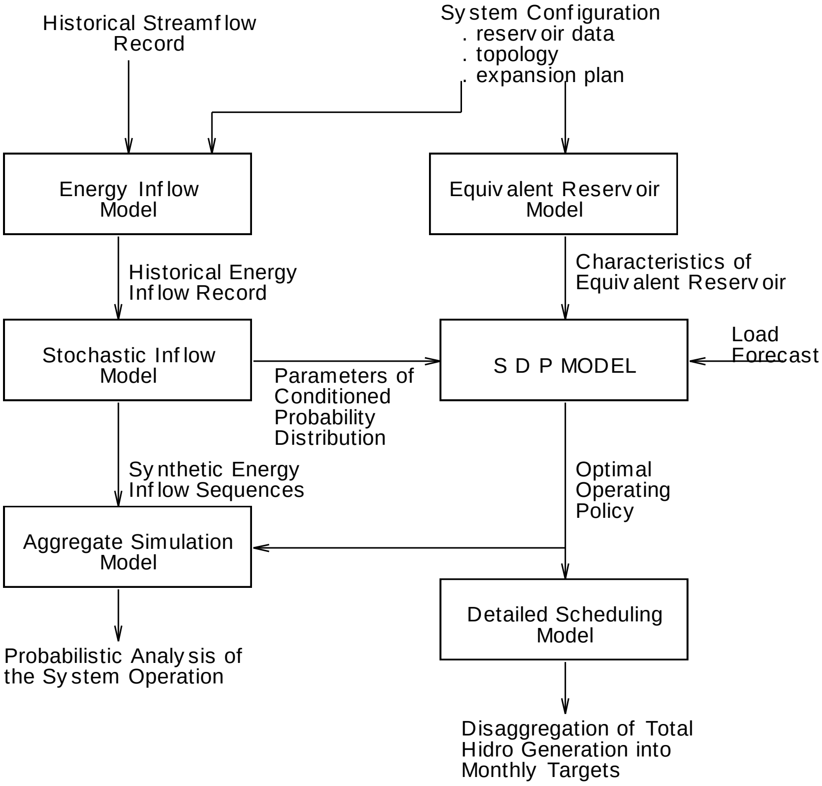
Appendices

Appendix 1. The Operations Planning Model



Source: Engercorp (1998c).

Appendix 2. Classification of Sectors according to Production Mode

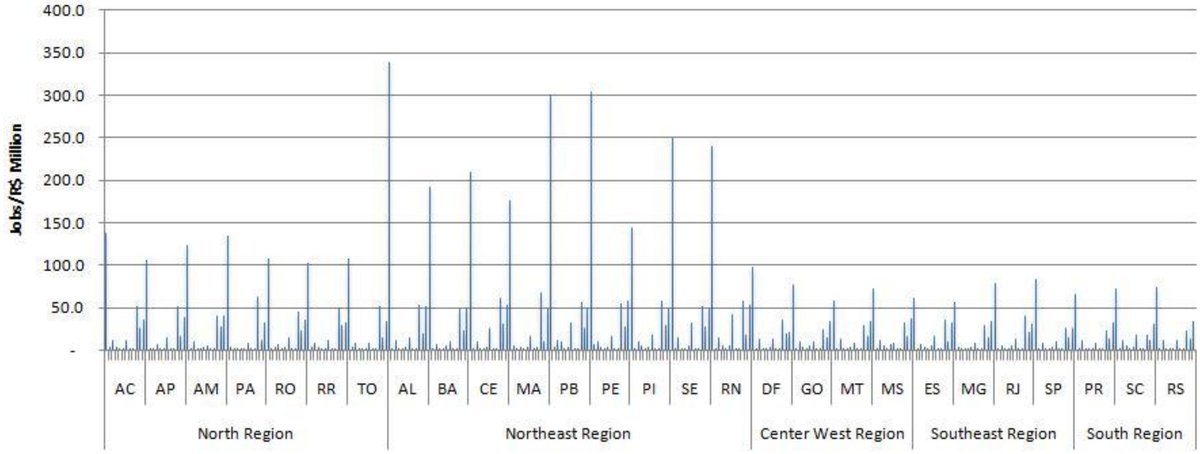
Sector	**Production Mode**
Agriculture	Antecipatory
Mining	Antecipatory
Siderurgy Industry	Antecipatory
Chemistry Industry	Antecipatory
Cement Manufacturing	Antecipatory
Nonferrous Metal Metallurgy (mainly aluminum)	Antecipatory
Other Industries	Responsive
Electric Energy Sector	Responsive
Air Transportation	Responsive
Truck Transportation	Responsive
Transportation – Others	Responsive
Other Sectors	Responsive

Appendix 3. Estimated Cost Structure for Osório Wind Farm (2004)

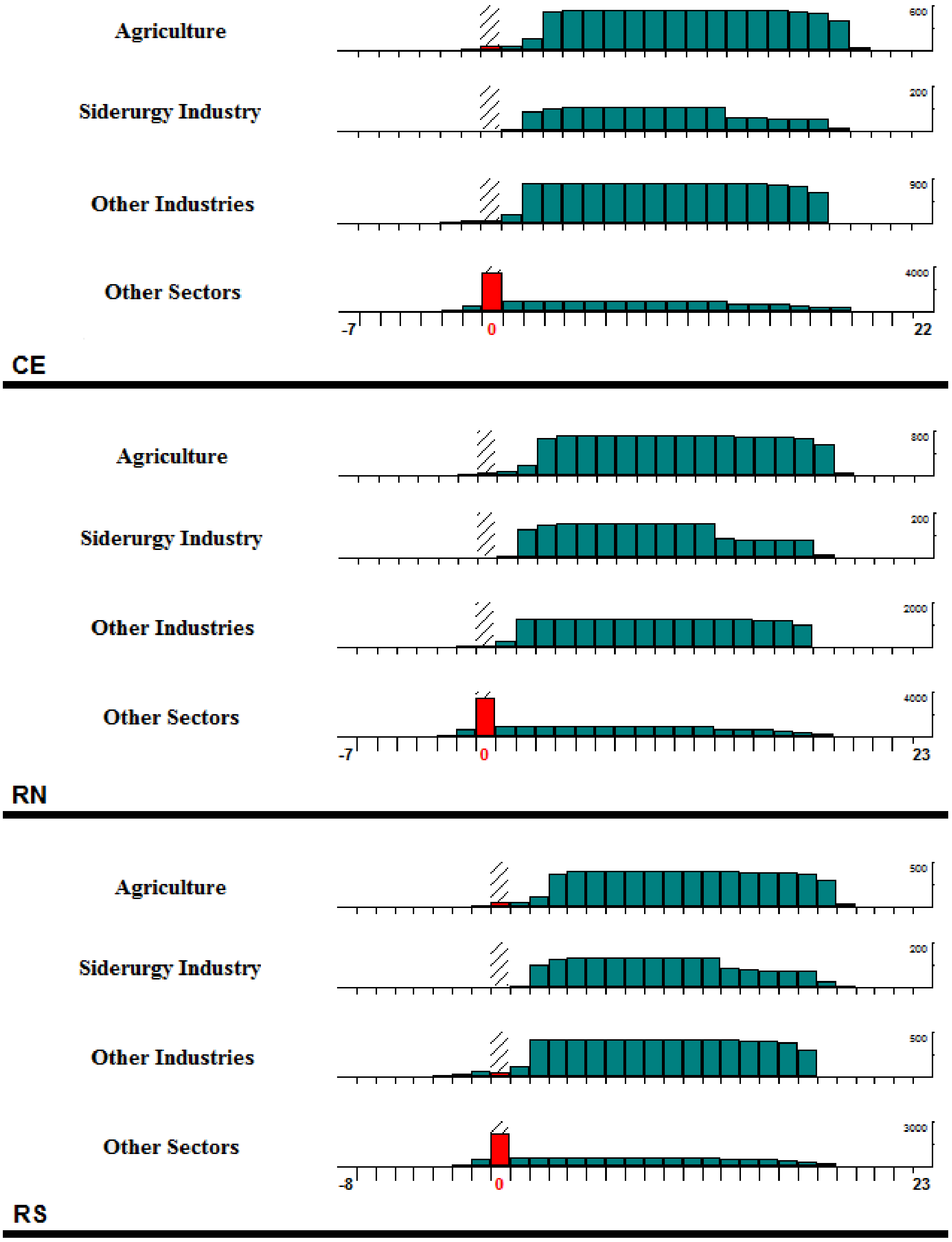
	Expenses %	R$
Construction	22%	
Concrete		R$ 12,222,214.09
Steel		R$ 11,151,818.18
Iron		R$ 11,151,818.18
Civil Construction		R$ 112,874,149.55
		R$ 147,400,000.00
Towers	10%	
Concrete		R$ 19,223,288.18
Steel		R$ 47,776,711.82
		R$ 67,000,000.00
Interesting rates during construction	4%	**R$ 26,800,000.00**
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 Engineering	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

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

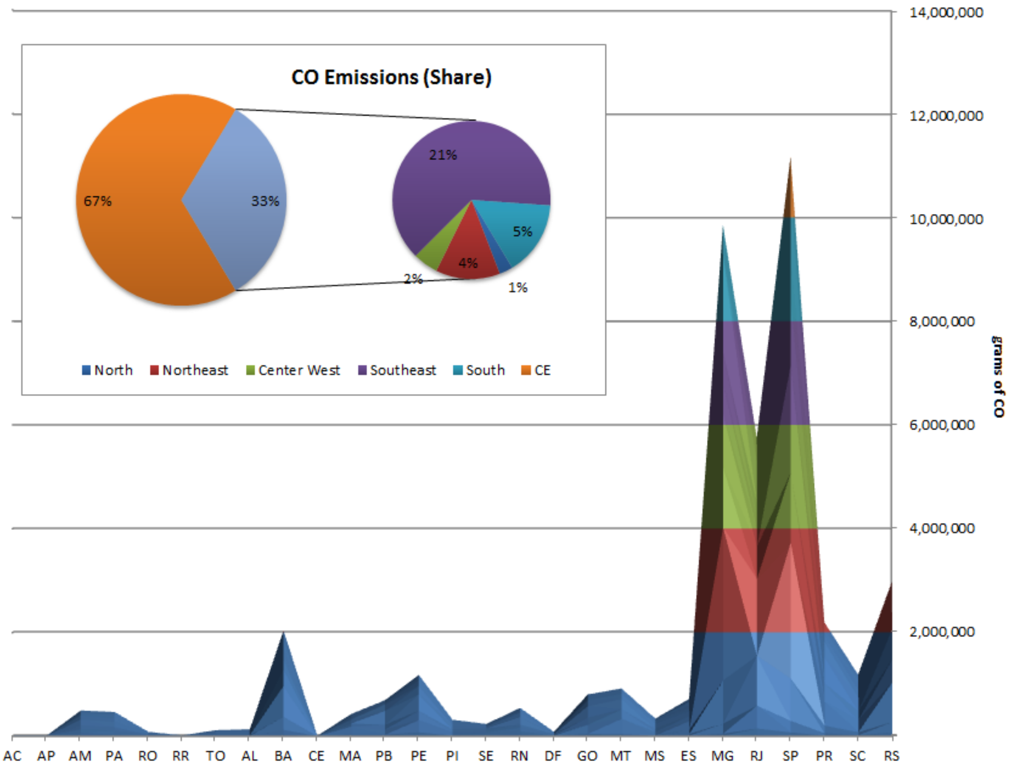
Appendix 4. Employment Coefficients by State



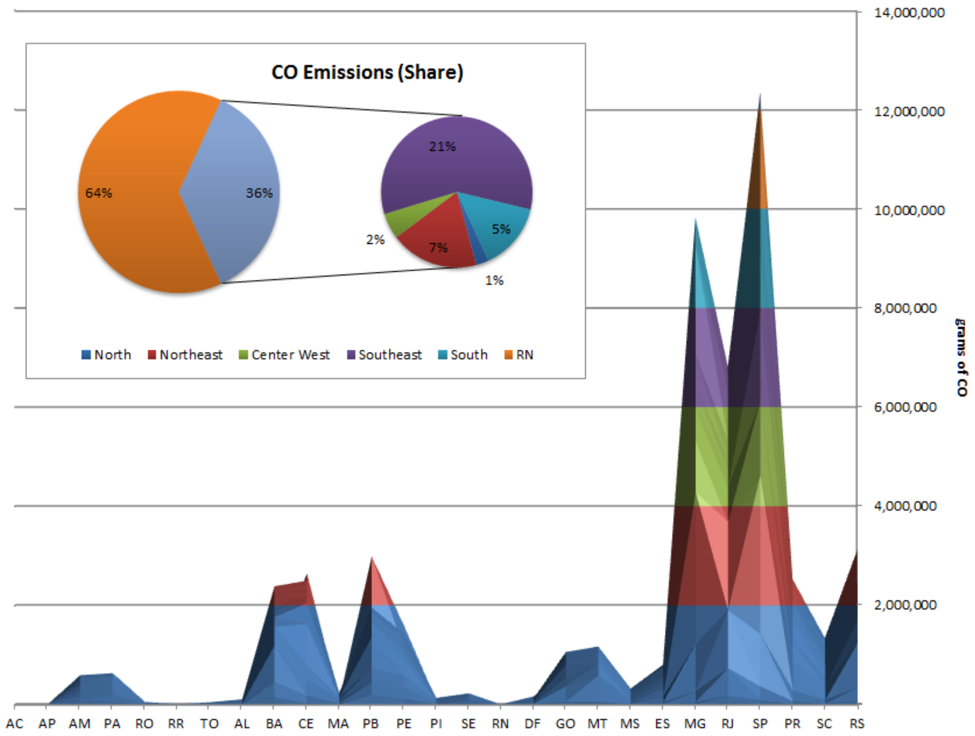
Appendix 5. Employment Dynamic through Time, Main Sectors



Appendix 6. CO Emissions by State and Total Share, CE (CE emissions removed)



Appendix 7. CO Emissions by State and Total Share, RN (RN emissions removed)



Appendix 8. CO Emissions by State and Total Share, RS (RS emissions removed)