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Publication Date

2019-03-01

DOI

10.1016/j.envint.2019.01.029

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Peer reviewed



EPA Public Access

Author manuscript

Environ Int. Author manuscript; available in PMC 2020 May 15.

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Published in final edited form as:

Environ Int. 2019 March ; 124: 420–430. doi:10.1016/j.envint.2019.01.029.

Health benefits and control costs of tightening particulate matter emissions standards for coal power plants - The case of Northeast Brazil

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Abstract

Exposure to ambient particulate matter (PM) caused an estimated 4.2 million deaths worldwide in 2015. However, PM emission standards for power plants vary widely. To explore if the current levels of these standards are sufficiently stringent in a simple cost-benefit framework, we compared the health benefits (avoided monetized health costs) with the control costs of tightening PM emission standards for coal-fired power plants in Northeast (NE) Brazil, where ambient PM concentrations are below World Health Organization (WHO) guidelines. We considered three Brazilian PM₁₀ (PM_x refers to PM with a diameter under x micrometers) emission standards and a stricter U.S. EPA standard for recent power plants. Our integrated methodology simulates hourly electricity grid dispatch from utility-scale power plants, disperses the resulting PM_{2.5}, and estimates selected human health impacts from PM_{2.5} exposure using the latest integrated exposure-response model. Since the emissions inventories required to model secondary PM are not available in our study area, we modeled only primary PM so our benefit estimates are conservative. We found that tightening existing PM₁₀ emission standards yields health benefits that are over 60 times greater than emissions control costs in all the scenarios we considered. The monetary value of avoided hospital admissions alone is at least four times as large as the corresponding control costs. These results provide strong arguments for considering tightening PM

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The authors declare no competing financial interest.

emission standards for coal-fired power plants worldwide, including in regions that meet WHO guidelines and in developing countries.

Keywords

Health impacts; Pollution control costs; Particulate matter; Emission standards; Coal power plants; Electricity grid dispatch; Air quality; Energy policy

1. Introduction

The combustion of fossil fuels is increasingly of concern, not only because of greenhouse gas emissions, but also because of the adverse health impacts of the air pollutants it produces. For coal, these pollutants include sulfur dioxide, nitrogen oxides, carbon monoxide, heavy metals such as mercury, and particulate matter (Smith et al., 2013). We focus here on particulate matter (PM), a complex mixture of tiny solid particles and liquid droplets emitted from both natural and anthropogenic sources, because of all the common air pollutants it is the largest contributor to global mortality and morbidity. PM, and especially PM_{2.5} (PM_x denotes particulate matter with a diameter under x micrometers), contains inhalable particles small enough to penetrate deep in the respiratory system, resulting in respiratory (e.g., asthma aggravation) and cardiovascular morbidity, and mortality from cardiovascular, lung cancer, and respiratory diseases (WHO, 2013). As a result, ambient PM_{2.5} is now the fifth largest contributor to global disease (Brauer et al., 2015). The impact of PM pollution has been worsening: between 1990 and 2015, the number of deaths attributable to ambient PM_{2.5} exposure increased from 3.5 million to 4.2 million (Cohen et al., 2017). However, PM emissions standards for coal-fired power plants - a large source of anthropogenic PM (National Research Council, 2010) - vary widely, depending on plant size, age, technology, and jurisdiction (Zhang, 2016).

A number of studies have quantified air quality and/or health impacts from fossil fuel power plants under various scenarios and control strategies at the regional (Levy et al., 1999, 2002a–2002b; Levy and Spengler, 2002; Zhou et al., 2003; Frost et al., 2006; Carbonell et al., 2007; Hao et al., 2007; Carreras-Sospedra et al., 2010; Vutukuru et al., 2011; McDonald-Buller et al., 2016) and national (Zhou et al., 2006; Markandya and Wilkinson, 2007; Levy et al., 2009; Machol and Rizk, 2013; Mokhtar et al., 2014; Driscoll et al., 2015) levels. A few studies have modeled hourly electricity grid unit commitment and dispatch to better capture the link between electricity production and ambient air concentrations (Kerl et al., 2015; Buonocore et al., 2016a–2016b; Rodgers, 2016); however, these studies used linear approximations to model the relationship between pollutant exposure and health impacts, which tend to underestimate health impacts at low concentrations and overestimate health impacts at high concentrations, compared to non-linear exposure-response models (Apte et al., 2015). We did not find any studies that combined hourly electricity grid unit commitment and dispatch with atmospheric dispersion and non-linear exposure-response models.

Several studies have compared the health benefits with the control costs of reducing various types of power plant emissions. Some papers focused on the acid rain program in the U.S.

After analyzing this program, Burtraw et al. (1998) reported that its health benefits outweigh its expected costs with a high level of confidence. In a subsequent investigation, Chestnut and Mills (2005) confirmed that the health and environmental benefits of the U.S. acid rain program (~US\$100 billion annually) dwarf its costs (~US\$3 billion annually). Burtraw et al. (2001) analyzed instead the cost-effectiveness of reducing NO_x emissions from electric power plants; they concluded that the benefits of the U.S. EPA mandated state implementation plans would more likely exceed costs with an annual cap than with a seasonal cap. More recently, Buonocore et al. (2016a) found that the net health benefits of the U.S. Clean Power Plan, which decreases emissions of various air pollutants (including PM) as a result of implementing a CO₂ standard, are in the order of US\$12 billion annually.

In China, Li et al. (2004) obtained a benefit-cost ratio ranging from 1 to 5 for reducing PM₁₀ emissions from coal-fired power plants in the heavily polluted Shanghai area. In a more recent study of several heavily polluted Chinese cities, Zhang et al. (2015) reported that the health benefits of reducing coal power plant emissions are 29 to 32 times greater than the corresponding control costs. Also of interest is the multi-continent cost-benefit analysis of local air pollution and global climate change by Bollen et al. (2009), who estimated that the benefit-cost ratio of controlling power plant emissions ranges from 2 to 32.

While these studies cover a broad array of contexts, to our knowledge no published study has yet combined hourly electricity grid unit commitment and dispatch simulations with atmospheric dispersion and a non-linear exposure-response model. In this paper, we adopt a conceptually simple cost-benefit framework to explore if different PM₁₀ emission standards are sufficiently stringent (i.e., if incremental benefits from tightening these standards are “close” to the corresponding control costs). We apply this framework to compare the health benefits (avoided health costs) and the control costs of tightening PM₁₀ emission standards for coal power plants in Northeast (NE) Brazil, where ambient PM concentrations are below World Health Organization guidelines (WHO, 2018).

Apart from our methodology, which is well-suited for areas that do not have the emissions inventories required by photochemical models to simulate secondary PM formation,¹ our paper makes several contributions. First, we provide new (conservative) benefit estimates of tightening PM standards based on the monetarily value of health benefits, which we compare with emissions control costs. Second, our case study adds to the thin literature dealing with the health impacts of thermal power plants in Latin America, which currently consists of two studies in Brazil (Alves and Uturbey, 2010; Avelino et al., 2015), one in Mexico (Lopez et al., 2005), and another one for three large Latin American cities (Bell et al., 2006). Third, while many previous studies have focused on areas with high PM concentrations (Zhou et al., 2003, 2006; Li et al., 2004; Bell et al., 2006; Hao et al., 2007; Guttikunda and Jawahar, 2014; Zhang et al., 2015), our case study is in a region where annual average ambient PM_{2.5} concentrations are below the WHO air quality guideline of 10 µg/m³ (WHO, 2018). Fossil fuel power plants in such areas are probably less likely to be

¹PM can either be emitted directly into the air (primary PM, which has both man-made and natural sources) or be formed in the atmosphere (secondary PM) from gaseous precursors such as SO₂, NO_x, ammonia, and nonmethane volatile organic compounds (WHO, 2013).

upgraded to curb emissions of air pollutants and the local population may erroneously feel safe from adverse health impacts caused by air pollution.

2. Methods and data

2.1. Study area

Our study area is in the northeast of Brazil (NE Brazil), a country that relies on renewable energy (mainly hydroelectricity) for over 80% of its electricity production (REN21, 2017).

NE Brazil is comprised of nine states that span over 1.5 million km² and have a combined population of 54 million people (Instituto Brasileiro de Geografia e Estatística, n.d.); see Fig. 1. The main cities of NE Brazil, Recife, Fortaleza and Salvador, have populations of 3.69, 3.61, and 3.57 million respectively (Instituto Brasileiro de Geografia e Estatística, n.d.).

NE Brazil, a semi-arid region, has some of the world's highest capacity factors for wind and solar electricity production, along with a large hydroelectric potential (Krauter, 2005; da Silva et al., 2016). Renewable electricity (including hydroelectricity) in Brazil is planned to expand from 103.1 GW of installed capacity in 2013 to 164.1 GW in 2023, while non-renewable electricity is forecasted to expand from 21.3 GW to 31.7 GW over the same time period (a total capacity increase of 57.3% over 10 years).

The NE grid is one of five large grids in Brazil's national interconnected power system (Brazil also has an isolated system in the Amazon Region). Its total installed capacity exceeds 29,000 MW, and its annual electricity demand tops 85,000 GWh (ONS, n.d.). Table 1 shows the installed capacity of electric generators regulated by the central dispatch authority Operador Nacional do Sistema Elétrico (ONS) in NE Brazil.

NE Brazil has only two large coal power plants: Porto do Pecém I (two 360 MW units) and Porto do Pecém II (one 360 MW unit). Both are located within 30 km of the Fortaleza metropolitan area (Fig. 1), along with several diesel and gas power plants. The location of these plants motivated our selection of the Fortaleza area for this study.

A review of regulatory documents indicates that Brazil has at least three different PM₁₀ emission standards (but currently no PM_{2.5} standard) for coal power plants: 28.15 g/kWh (Ministério de Minas e Energia, 2007); 390 mg/Nm³ (0.69 g/kWh; National Counsel of the Environment (CONAMA)) (Ferreira, 2015); and 204 mg/Nm³ (0.36 g/kWh; for power plants funded by Brazil's National Development Bank (BNDES)) (Governo do Estado do Ceará, n.d.). We were unable to determine why the PM₁₀ emission standard in the 2030 National Energy Plan is so much higher than the other emission standards. The CONAMA and BNDES standards were converted to g/kWh using data from the Porto do Pecém power plants. By comparison, the U.S. EPA PM₁₀ emission standard for electric utility steam generating units over 73 MW built after 05/03/11 is 0.09 lb./MWh (0.04 g/kWh or 22.6 mg/Nm³) (U.S. EPA, 2015), which is among the most stringent standards in the world (Zhang, 2016).

This sets the stage for our study. We analyzed the health benefits and control costs of the following three scenarios:

- Scenario 1: the PM₁₀ emission standard is cut from 28.15 g/kWh to 0.69 g/kWh;
- Scenario 2: the PM₁₀ emission standard is reduced from 0.69 g/kWh to 0.36 g/kWh; and
- Scenario 3: the PM₁₀ emission standard is tightened from 0.36 g/kWh to 0.04 g/kWh.

2.2. Integrated assessment methodology

Fig. 2 present an overview of our integrated methodology. First, we modeled hourly unit commitment and dispatch of the NE Brazil electricity grid level for an entire year (2015).

Second, we dispersed the resulting hourly primary PM_{2.5} emissions (after converting PM₁₀ emissions using the PM_{2.5}/PM₁₀ ratio as explained in Subsection 2.2.2) for year 2015 using the dispersion model CALPUFF ViewTM. We did not consider secondary PM because the natural and anthropogenic emissions inventories required to simulate secondary PM formation are not available in our study area, which makes our results conservative.

Third, the resulting PM₂₅ concentrations were processed in BenMAP (U.S. EPA, 2017a) using the latest IER model (Cohen et al., 2017) to capture the non-linear relationship between pollutant exposure and health impacts. The monetized health benefits were then compared with the emission control costs, which we calculated using an integrated environmental control model (Carnegie Mellon University, 2017).

2.2.1. Electricity system dispatch model (PLEXOS[®])—To model hourly power plant dispatch for a whole year (2015), we built a spatially and temporally resolved electricity dispatch model for the electric grid of Northeast (NE) Brazil using the PLEXOS[®] model. Recent studies have used PLEXOS[®] to assess large-scale renewable integration (Palchak et al., 2017), capacity expansion planning (Shirley and Kammen, 2015), and pumped storage hydropower (Koritarov et al., 2014).

Electricity dispatch models simulate optimal power plant dispatch to match load (i.e. electricity demand) and generation (i.e. electricity supply), while accounting for the marginal cost of electricity generation and technical, economic, and environmental constraints. We selected PLEXOS[®] because it has a broad range of functionalities, an intuitive user interface, and an extensive documentation. Alternatives to PLEXOS[®], such as the NEWAVE model developed by Brazil's Power Sector Research Center (CEPEL), are proprietary and therefore unavailable.

Designing an electricity dispatch model that optimizes unit commitment requires defining load, a transmission network, generators, fuels, emissions, storages, reserves, and various constraints. As load profiles are not public in Brazil, we also had to develop an hourly load profile for NE Brazil for 2015 by projecting to 2015 the 2013 NE Brazil load profile obtained from Brazil's National System Operator (ONS, Operador Nacional de Sistema

Eletrico). We relied on the load forecasting algorithm in PLEXOS[®], and assumed that electricity demand grows by 4.77% per year (Torrini et al., 2016).

Transmission system data were obtained from Miranda et al. (2017), who recently studied the integration of large-scale wind power into the NE Brazil electricity grid. Each generator (node) was connected to a transmission line, and each transmission line was constrained by its maximum flow capacity.

We modeled all of the 393 generators in NE Brazil that are centrally dispatched by Brazil's ONS (Table 1). For each generator, a set of properties was defined, as shown in Fig. 3. Most of the data used for developing our NE Brazil PLEXOS[®] model were collected by our partners at the Center for Energy and Environmental Economics (CENERGIA) at the Universidade Federal do Rio de Janeiro. These data were sourced primarily from Brazil's national electricity operation authority ONS and from the national electricity regulator ANEEL (Agência Nacional de Energia Elétrica). Additional data were obtained directly from ONS and ANEEL.

Hydroelectric power plants, which represent 49.8% of NE Brazil's electric system capacity, were dispatched to minimize the cost of thermal generation over our period of analysis. Each hydroelectric plant was constrained by setting the initial fill level of each reservoir to the percentage of NE hydro storage capacity that each reservoir contributes, multiplied by the stored energy in January 2015. The final level of each reservoir was set to the percentage of NE hydro storage capacity that each reservoir contributes, multiplied by the stored energy in December 2015. Moreover, the maximum energy available per month for each hydroelectric plant was based on prior year hydroelectric dispatch records to account for seasonality in precipitation patterns and electricity demand (Energy Exemplar, n.d.).

Following previous studies (e.g., Blair et al., 2014), the hourly generation of wind and solar power plants across NE Brazil was simulated based on location specific wind speeds and solar irradiation profiles. We relied on a CENERGIA wind generation model and the United States National Renewable Energy Laboratory System Advisory Model (Blair et al., 2014).

Properties specific to each thermal generator include maximum capacity, heat rate, minimum stable level, ramp up and ramp down rates, minimum uptime and downtime, start time and emissions rates.² PM₁₀ emission rates were based on PM₁₀ emission standards in the Ministry of Mines and Energy 2030 Energy Plan (2007): 0.042 g/kWh for natural gas generators, 0.37 g/kWh for diesel generators and 0.49 g/kWh for biomass generators. For coal power plants, we used the PM₁₀ emission standards discussed above (28.15 g/kWh, 0.69 g/kWh, 0.36 g/kWh, and 0.04 g/kWh). We simulated the NE Brazil electric grid dispatch and emissions under each of the four PM₁₀ emission standards considered, holding all other properties of the NE Brazil electricity system constant between simulations. Hourly

²Maximum capacity is each generator's installed capacity. The heat rate is the amount of fuel required to produce one unit of electricity (MJ/kWh). The minimum stable level is the minimum stable generation. Ramp up/down rates limit the rate at which generation can increase/decrease (MW/min). The minimum up/down time is the minimum number of hours a generator must be left on or off for in any commitment cycle. The start time is the amount of time each generator requires to reach its minimum stable level. Emission rates are the rate of production of air pollutant emissions (g/kWh).

emissions were calculated for each power plant based on actual dispatch, assuming that all thermal power plants abide by the relevant emission standard for the scenario considered.

After simulating NE Brazil's electricity grid dispatch for year 2015, spatially resolved emission profiles containing the time-varying hourly emissions for each generator (8760 entries per generator) were entered into CALPUFF View™.

2.2.2. Atmospheric dispersion of PM emissions (CALPUFF)—We selected CALPUFF for simulating the dispersion of primary PM emissions because it is widely used, extensively validated, recommended by the U.S. EPA (U.S. EPA, 2017b), and well suited for this study. CALPUFF is a non-steady-state Lagrangian Gaussian puff model that accounts for complex terrain effects, overwater transport, long-range transport, coastal interactions, building downwash, wet and dry removal, and simple chemical transformations. CALPUFF View™ (the commercial version of CALPUFF we used; Lakes Environmental, n.d.) includes built-in modules for processing input data (meteorological data, geophysical terrain) and results from the dispersion of selected pollutants.

Dispersion modeling for our study required spatially resolved power plant emissions, meteorological, and topographic data. NE Brazil fits in a 1200 km by 1500 km rectangle. We selected a 320 km × 320 km area with a 5.4 km × 5.4 km grid around Fortaleza to capture air quality changes caused by the PM emissions of thermal generators in that area, which include the only two large coal power plants in NE Brazil. Out of the 39 operational thermal power plants in NE Brazil in 2015 (Table 1), eight are within our study area.

Hourly meteorological conditions for our study area were developed as WRF (weather research and forecasting) files with a 4 km resolution by the University of Waterloo, Canada. The WRF files include surface meteorological data, such as wind speed and direction, temperature, surface pressure, precipitation and cloud cover, as well as vertical profiles of wind speed and direction, temperature, and pressure.

We processed the WRF meteorological data in CALMET (a module of CALPUFF View™) to develop wind and temperature fields on a three-dimensional grid with a 4 km resolution. To process geophysical terrain inputs for CALMET, we used three publicly available map files (SRTM1, SRTM3 and GTOPO30) to account for land and ocean effects, because Fortaleza and the Porto do Pecém power plants are close to the Atlantic coast.

The PM₁₀ emissions simulated in PLEXOS® were converted to PM_{2.5} using the ambient ratio method (Boldo et al., 2006) before dispersion in CALPUFF View™. For this conversion, we calculated a ratio by mass of primary PM_{2.5}/PM₁₀ of 0.775 by averaging all reported PM_{2.5} to PM₁₀ emissions (by mass) for coal, oil, and natural gas generation in the United States (U.S. EPA, 2018a) as suitable Brazilian data were not available. As the ratio PM_{2.5}/PM₁₀ varies by fuel source, it was weighted for each fuel source based on their contribution to emissions in the NE Brazil electric grid.

2.2.3. Health outcomes modeling (BenMAP)—To assess how changes in long-term human exposure to PM_{2.5} concentrations affect selected health outcomes, we used the U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) (U.S. EPA,

2017a). We are aware of a dozen of multinational air pollution health impact assessment tools but we chose BenMAP for its versatility. BenMAP performs spatial and temporal calculations based on differences in air pollution concentrations between a baseline and a control scenario. It then combines concentration changes with spatially resolved population and baseline disease incidence data and uses concentration-response (C-R) functions to estimate the number of people affected (and the cost) for various health outcomes.

Population data with a 10 km × 10 km resolution for 2015 were extracted from the BenMAP regional datasets (U.S. EPA, 2017c) sourced from the United Nations Socioeconomic Data and Applications Center (SEDAC). We did not use Brazilian census data because the finest available resolution (municipality level) is coarser than the SEDAC data. Baseline disease incidence data and ambient PM_{2.5} concentrations were also downloaded from the BenMAP regional datasets. Both population and disease incidence data were discretized into 16 age groups using the 2015 Brazilian age pyramid (a graph showing the distribution of a population [on the horizontal axis] by age [on the vertical axis] and gender, with men on the left and women on the right) to match the requirements of the C-R functions we used.

We collected ambient PM_{2.5} concentrations, which ranged from 5 to 10 µg/m³, from the 2013 Global Burden of Disease (Brauer et al., 2015). To combine the 5.4 km × 5.4 km PM_{2.5} air quality concentrations (simulated in CALPUFF View™) from electric grid emissions with the 10 km × 10 km PM_{2.5} ambient concentrations, we interpolated ambient PM_{2.5} concentrations using inverse-distance weighting (see Fig. 4 Panel D) because it has been shown to be preferable to Kriging or Thiessen polygons for environmental data (Akkala et al., 2010). We assumed that ambient concentrations reflect PM_{2.5} emissions under the 0.36 g/kWh standard because BNDES provided funding to the Porto do Pecém coal power plants to meet this standard (Governo do Estado do Ceará, n.d.). Therefore, the PM_{2.5} power plant emissions under the 0.36 g/kWh standard were subtracted from the ambient concentrations in all scenarios before adding the simulated power plant emissions.

To estimate premature mortality, we relied on the 2017 global IER model (Cohen et al., 2017). The IER model is the only model that spans the entire global range of PM_{2.5} exposure for the five main causes of PM-related mortality, which is necessary to capture the effects of high PM_{2.5} air quality concentrations in Scenario 1. In a study comparing the IER model with seven other prediction methods previously used in burden assessments, the IER model was found to be the best predictor of relative risk changes due to PM_{2.5} exposure (Burnett et al., 2014). Table 2 presents the C-R functions used to estimate mortality and hospital admissions.

As shown in Table 2, we relied on epidemiological studies from the U.S. and Europe, because for many health endpoints Latin American results are not available for PM_{2.5} (Bell et al., 2006). To assess the impact of using a different C-R function, we also quantified premature mortality using a PM_{2.5}C-R function developed by Lepeule et al. (2012) for low PM_{2.5} concentrations in the US, which matched the range of ambient PM_{2.5} concentrations in NE Brazil (see the sensitivity analysis section below).

We derived valuation functions for each type of hospital admission considered by updating the standard BenMAP cost of illness valuation functions for hospital admissions with Brazil hospital costs. Brazilian hospital admissions costs were sourced from a World Bank study (La Forgia and Couttolenc, 2008) and updated to 2015 using the Brazilian medical wage index (World Bank, n.d.). All of our health benefits and control costs are expressed in 2015 US\$.

To calculate the value of a statistical life (VSL) for Brazil for 2015, we followed the U.S. EPA (2018b) recommended approach:

$$Brazil\ VSL_{2015} = US\ VSL_{2015} * \left(\frac{Brazil\ GDPPC_{2015}}{US\ GDPPC_{2015}} \right)^{0.8} * Brazil\ PPP_{2015}, \quad (1)$$

where GDPPC denotes the gross domestic product per capita (obtained by dividing the gross domestic product, adjusted for purchasing parity, by the total population); and *Brazil* PPP_{2015} is the purchasing power parity conversion factor for Brazil, i.e., the number of units of Brazil's currency required to buy the same amounts of goods and services in Brazil as \$1 in the U.S.

The U.S. EPA (2018b) recommends a U.S. VSL for 2015 of \$10 million. For 2015, the Brazil and U.S. GDPPC were respectively \$15,615 and \$56,207 in PPP-adjusted dollars, and the PPP GDP conversion factor for Brazil was 1.9 (World Bank, n.d.). The 0.8 exponent comes from the OECD (2012), and represents the elasticity between income and willingness to pay to avoid adverse health effects. The resulting 2015 VSL for Brazil is US\$6,819,641.

2.2.4. Emission control costs—To compare the avoided health costs (health benefits here) from tightening the PM_{10} emission standard with the corresponding control costs for the two Porto de Pecém coal power plants in our study area, we analyzed control costs using the Integrated Environmental Control Model (IECM) (Carnegie Mellon University, 2017). Our analysis relied on plant specific data, including plant capacity, plant life, and coal type. We considered the two post-combustion particulate controls for coal power plants available in the IECM: cold-side electrostatic precipitators (ESP) and fabric filters (FF), whose $PM_{2.5}$ collection efficiency is 98.0% and 99.7% respectively (Zhang, 2016).

Capital costs include particle collectors, ductwork, fly ash equipment, fans, general facilities costs, engineering fees, pre-production costs, process contingency costs, and interests. Per net MW, capital costs total US\$47,170 for an ESP and US\$56,780 for a FF. Fixed costs include operating and maintenance labor, maintenance material and administrative labor. Per MWh, fixed costs sum to US\$0.3293 for an ESP and US\$0.4166 for a FF. Variable costs include electricity, water and waste disposal, for a total per MWh of US\$0.4790 for an ESP and US\$0.4986 for a FF.

The equipment and material costs were assumed to be 38.4% greater for Brazil than for the U.S., based on an estimate of the additional costs (freight and insurance costs, import fees, customs expenses and Brazilian taxes) of importing equipment (Köberle et al., 2018). Brazilian labor costs were assumed to be 21% of U.S. labor costs, based on the Brazil to U.S. gross national income per capita ratio.

We calculated that the annualized cost of removing 1 tonne (metric ton) of PM₁₀ is US \$87.98 with an ESP and US\$119.90 with a FF for a 360 MW unit. To estimate the control costs of reducing PM₁₀ emissions Scenarios 1 and 2, we assumed that an ESP would be used because this approach is cheaper and sufficiently efficient (98.0% PM_{2.5} removal efficiency). Since Scenario 3 requires that 99.0% of PM₁₀ emissions be removed, we assumed a FF would be used because it has a 99.7% PM_{2.5} removal efficiency.

3. Results

3.1. Electric grid emissions

Results from our PLEXOS[®] simulations for 2015 show an annual system load of 96,385 GWh and an annual electricity generation of 97,593 GWh. Total simulated generation was 1.3% greater than load and the simulated hydroelectric generation was within 3.2% of actual hydroelectric generation. When generation is greater than load and no energy storage resources are available, electricity generation must be curtailed or dissipated into heat (dump energy). The dump energy in our simulations was 1218 GWh (1.3% of load) and the unserved load was only 10 GWh (0.01% of load) (10 GWh = 96,385 + 11,218 GWh – 97,593 GWh).

Table 3 displays total PM₁₀ emissions by standard from the entire NE Brazil electric grid for 2015. It shows that emissions from coal power plants in our study area could be reduced by 240,617 t of PM₁₀/year (=248,679-8062, or 96.8%) under Scenario 1, by 28921 of PM₁₀/year (=8062-5170, or 35.9%) under Scenario 2, and by an additional 28031 of PM₁₀/year (5170-2367, or 54.2%) under Scenario 3.

3.2. Resulting ambient air quality changes

Table 4 summarizes different mean PM_{2.5} concentrations from power plant emissions. The maximum annual mean PM_{2.5} concentrations are 91.7, 2.26, 1.18, and 0.35 µg/m³ under the 28.15, 1.18, 0.36, and 0.04 g/kWh standards respectively. We note that under the 0.69 g/kWh, 0.36 g/kWh and 0.04 g/kWh standards, PM_{2.5} concentrations in NE Brazil are below the World Health Organization (WHO) annual mean guideline of 10 µg/m³ PM_{2.5} and 24-hour mean guideline of 25 µg/m³ (WHO, 2018) even after accounting for ambient PM_{2.5} concentrations. These values illustrate the drastic reduction in PM_{2.5} under the 3 scenarios considered.

Panels A to D of Fig. 4 display average annual PM_{2.5} concentrations under each standard considered to illustrate how they change as PM₁₀ standards are being tightened. As expected, the highest average annual concentrations are closest to the coal power plants and disperse westerly, in accordance with the annual wind rose shown in Fig. 5. Panel E of Fig. 4 displays ambient PM_{2.5} concentrations for reference (described in Section 2.2.3). As explained above, the Porto de Pecém coal power plants are assumed to abide by the 0.36 g/kWh PM₁₀ standard.

PM_{2.5} concentration results from CALPUFF View[™] only account for power plant emissions in the region surrounding Fortaleza. The (grid cell-level) highest annual mean PM_{2.5} concentration is substantially less than the observed ambient PM_{2.5} concentrations under the

0.36 g/kWh and 0.04 g/kWh standards, which is expected because electricity grid emissions contribute only a portion of total ambient PM_{2.5}. Ambient concentrations were incorporated in the health outcomes modeling to assess the impact of air quality improvements on human health.

3.3. Human health impacts

Table 5 (and the abstract art figure) summarizes the expected health benefits and the control costs of tightening the PM₁₀ standard for coal power plants under each of the three scenarios considered. These results are based on average annual PM_{2.5} concentrations. Implementing Scenario 1 would prevent ~168 premature deaths and reduce hospital admissions by 16,257 cases per year, which is worth US\$1.264 billion per year with our assumptions. Cutting the PM₁₀ emission standard from 0.69 to 0.36 g/kWh (Scenario 2) would prevent an additional 3.7 premature deaths and 198 hospital admissions, which represents annual savings of US \$26.4 million. Further tightening the PM₁₀ emission standard from 0.36 to 0.04 g/kWh would avoid 4.2 premature deaths and 194 hospital admissions, for annual savings of US \$30.0 million.

Although premature deaths drive the value of health losses under the three scenarios considered, the number of additional hospital admissions is 46 to 97 times greater than the number of premature deaths as most people affected by PM_{2.5} pollution will suffer from respiratory ailments or cardiovascular disease.

3.4. Comparison of health benefits with emissions control costs

Our calculations show that tightening the PM₁₀ emission standard under Scenario 1 would cost US\$21.1 million per year and cut 240,617 t of PM₁₀. Going from 0.69 to 0.36 g/kWh (Scenario 2) would cost US\$0.25 million per year and decrease annual PM₁₀ emissions by 2892 t. Implementing Scenario 3 would cost US\$0.34 million per year and remove 2803 t of PM₁₀.

Although these amounts are substantial, they are dwarfed by the expected health benefits of reducing PM pollution. Indeed, the value of avoided health costs is respectively 60 times, 103 times, and 89 times greater than the cost of controlling emissions under Scenario 1, 2, and 3. These results reflect that the relative risk of disease incidence per unit increase in pollution is greater at low exposure than at high exposure (health impacts depend non-linearly on PM exposure concentrations) (Burnett et al., 2014). The costs of hospital admissions related to PM pollution are by themselves at least four times larger than the emission control costs.

3.5. Sensitivity analysis

Uncertainty was analyzed at each modeling stage. As hydroelectric plants represent 49.8% of NE Brazil's electricity infrastructure capacity (ONS, n.d.), we analyzed the impact that dry year conditions have on emissions by restricting reservoir levels and maximum energy dispatch to 2012 levels, which was the driest year in the NE Brazil water basin since 1983 (CHRS, 2016). As expected, total annual PM₁₀ emissions increased most for the more

stringent standards (e.g., by 18.5% under the 0.36 g/kWh PM₁₀ standard), and little under the 28.15 g/kWh standard.

During the air quality modeling stage, we compared concentrations obtained by converting PM₁₀ to PM_{2.5} before and after dispersion, which differed by an average of ~1% over the study area.

During our health impact analyses, we compared adult premature mortality cases from the IER model with the Lepeule et al. (2012) C-R function. The latter was developed for low PM_{2.5} concentrations (8–18 µg/m³) and has a higher relative risk estimate between PM_{2.5} exposure and mortality. We found that adult mortality cases were 2.9 to 4.9 times higher with the Lepeule C-R function, which further highlights that our results are conservative.

4. Conclusions

In this paper, we combined an hourly electric grid simulation model for year 2015 (built using PLEXOS[®]), with spatially resolved atmospheric dispersion (via CALPUFF View[™]), and human health impacts estimation for various health outcomes related to PM_{2.5} exposure (via BenMAP) to quantify the health benefits of tightening PM₁₀ standards and compare them to PM emissions control costs. We found that the value of avoided health costs is 60 times greater than the emission control costs when cutting the PM₁₀ emission standard from 28.15 g/kWh to 0.69 g/kWh (Scenario 1), 103 times greater when reducing it further from 0.69 g/kWh to 0.36 g/kWh (Scenario 2), and 89 times greater when tightening it from 0.36 g/kWh to 0.04 g/kWh, which is among the most stringent standards in the world (Zhang, 2016).

These results are noteworthy because they show that even in an area where ambient PM_{2.5} ambient concentrations are below the WHO guidelines, the local population would experience substantial health gains from tightening PM₁₀ emission standards.

Although a key driver of our results compared to some of the older studies (e.g., Li et al., 2004; Lopez et al., 2005; Pervin et al., 2008; Bollen et al., 2009) is the higher value of a statistical life (VSL), decreasing the VSL would not qualitatively change our conclusions that, from the point of view of society, stricter PM₁₀ standards for coal power plants should be implemented. Indeed, the mere benefit of avoiding PM-related illnesses leading to hospital admissions would exceed emission control costs by at least a factor four under each of the scenarios we considered.

Furthermore, it is important to note that the range of expected health benefits we report is conservative for several reasons. First, we did not account for secondary PM, although its impact could be quite substantial (Behera and Sharma, 2010), because modeling secondary PM requires complete natural and anthropogenic emissions inventories, which are not available for our study area (Sogabe, 2018). Second, we were not able to consider mortality induced by PM exposure in people aged 1 to 25 years because of epidemiological data limitations. Third, we note that lenient environmental regulations attract poorer quality investors (Dowell et al., 2000) and high-polluting joint ventures (Dean et al., 2005), which further degrade regional environmental quality and human health. Accounting for these

secondary effects would further tilt the balance in favor of more stringent PM emission standards.

Tightening standards is not sufficient, however. Standards need to be enforced, which can be challenging, especially in developing countries where plant-level monitoring data are rarely available (Barton et al., 2000).

In the future, it would be of interest to model secondary PM (when the necessary data become available) and to apply our methodology to areas with different geographic, demographic and electricity infrastructure conditions. Another avenue would be to explore the impact of even higher spatial resolution on results with appropriate terrain, meteorological, and population data, and to investigate seasonal variations in PM emissions and health impacts. Moreover, other pollutants could be modeled jointly with PM to analyze the co-benefits and costs of joint standards. Finally, it would be of interest to study the labor impacts of tightening PM₁₀ standards in NE Brazil, and more generally of increasing the share of renewable electricity.

Coal power plants will likely play an important role until the emergence of more cost-effective storage systems that can provide reliable base loads from renewable energy plants. However, the substantial difference between health benefits and control costs presented in this study argues strongly for tightening and enforcing the emission standards of coal power plants to improve local and regional air quality, not only in heavily polluted areas but also in relatively clean areas (where PM_{2.5} concentrations are below WHO guidelines), including in developing countries.

Acknowledgements

The first author is grateful to the National Science Foundation for a Graduate Research Fellowship under Grant No. DGE-1321846. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. Our co-authors in Brazil and Ecuador supplied the Brazilian electric system data and indispensable modeling advice. Our collaboration was funded by the NSF Graduate Research Opportunities Worldwide program and the United States Agency for International Development. Professor Jesse Thé provided the meteorological data and essential air quality modeling advice. Neal Fann supplied BenMAP data and gave invaluable advice through a collaboration funded by the NSF Graduate Research Internship Program. Energy Exemplar Pty Ltd. provided an academic license for the Plexos integrated energy model and Lakes Environmental Software provided software (including WRPLOT View) for air dispersion modeling; we are very grateful for these contributions.

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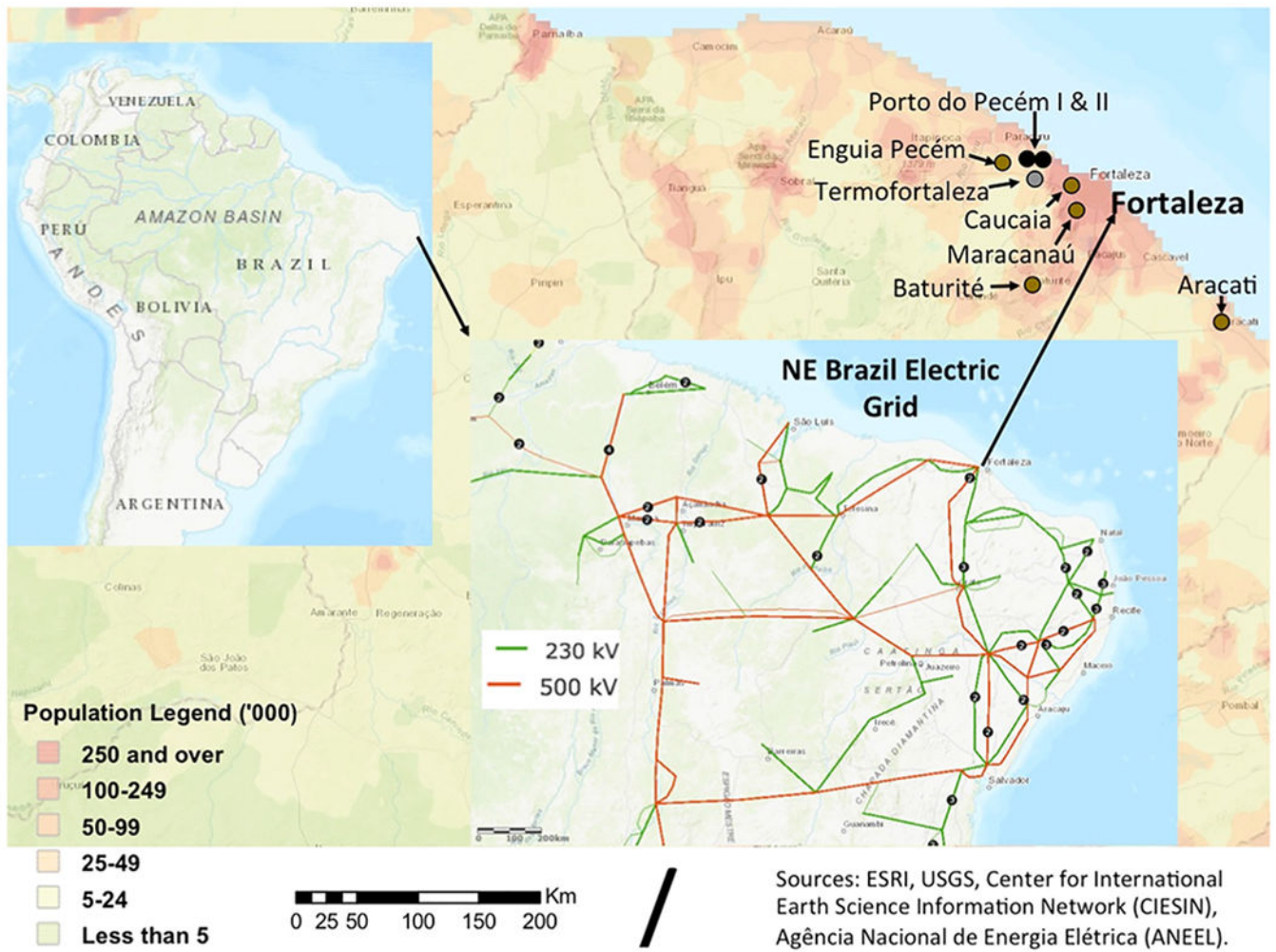


Fig. 1.
Study area.

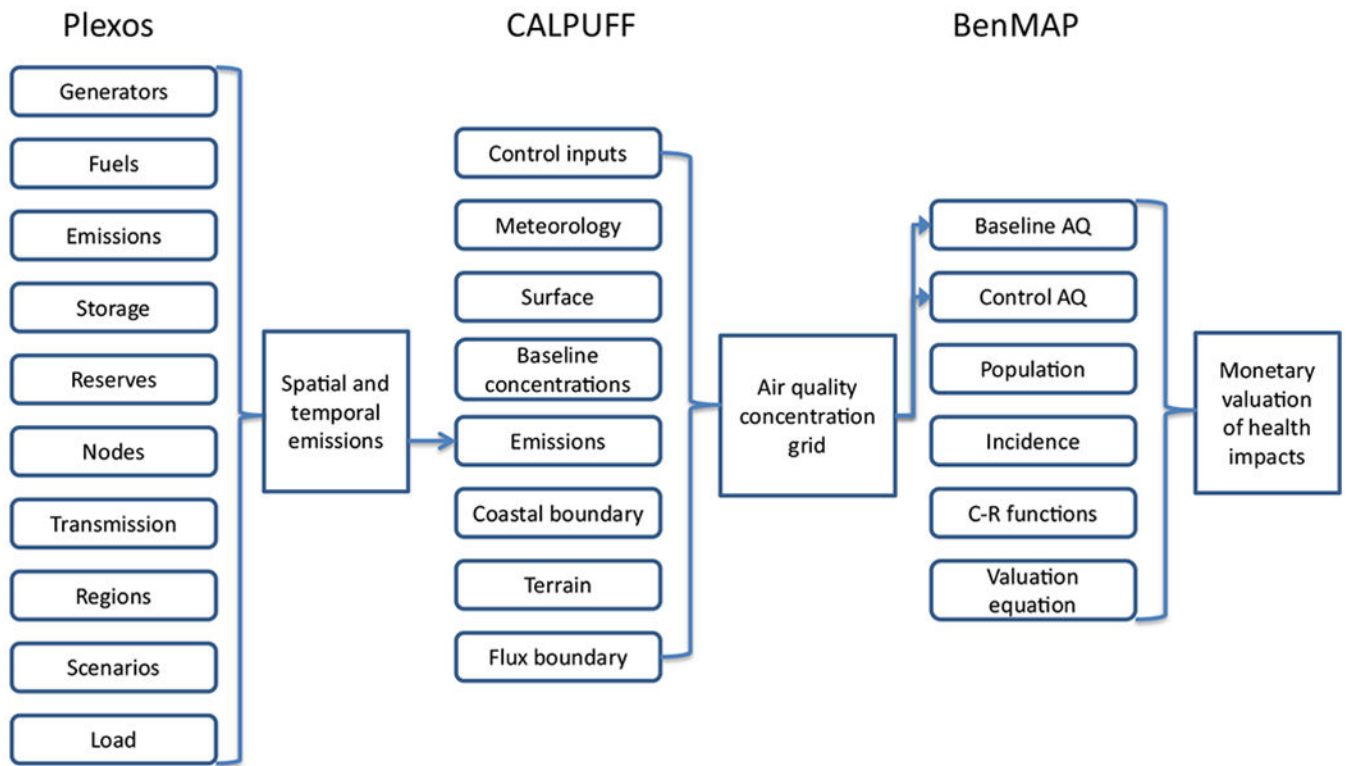


Fig. 2.
Methodology overview.

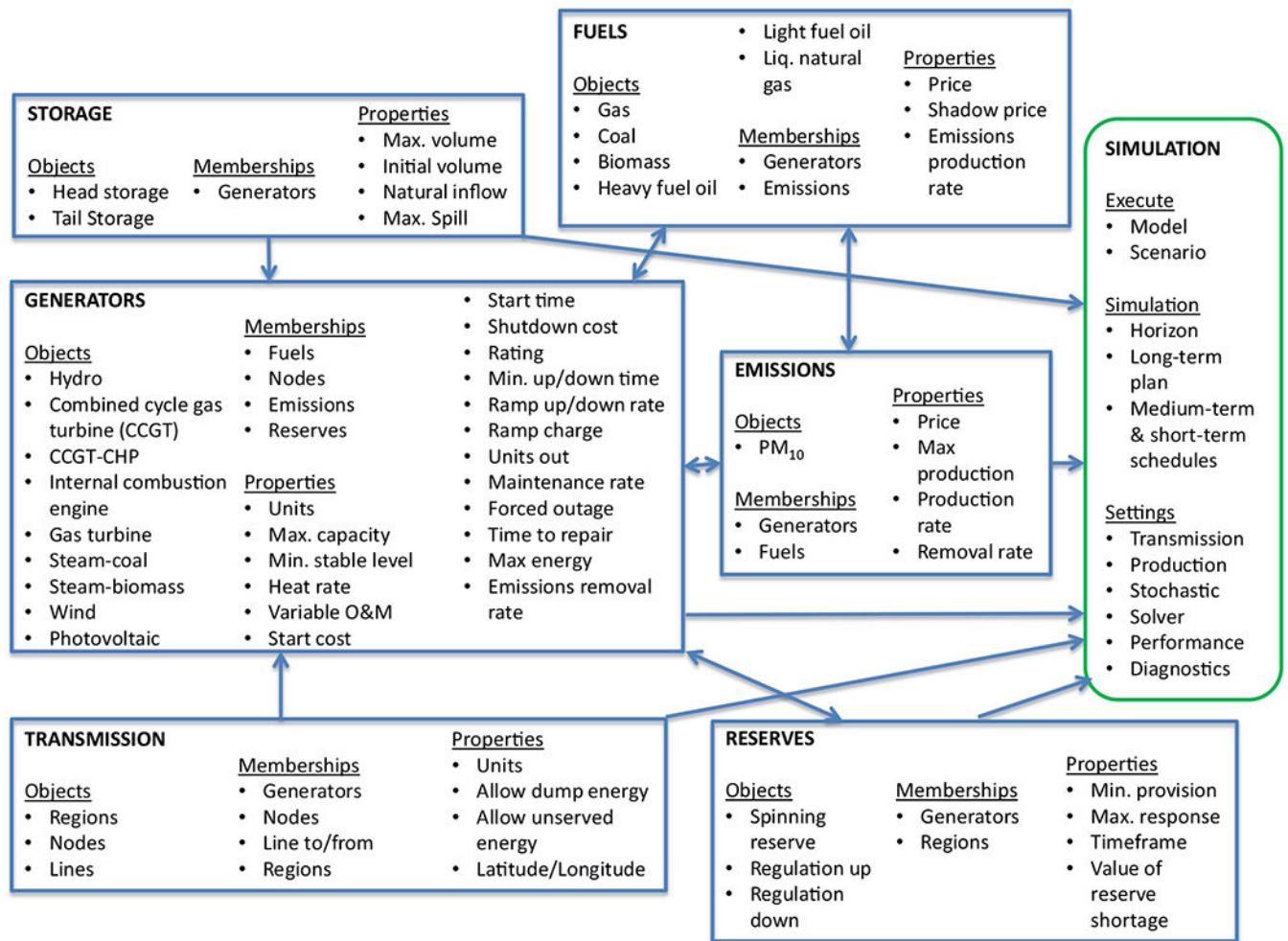


Fig. 3.
Electric grid simulation data.

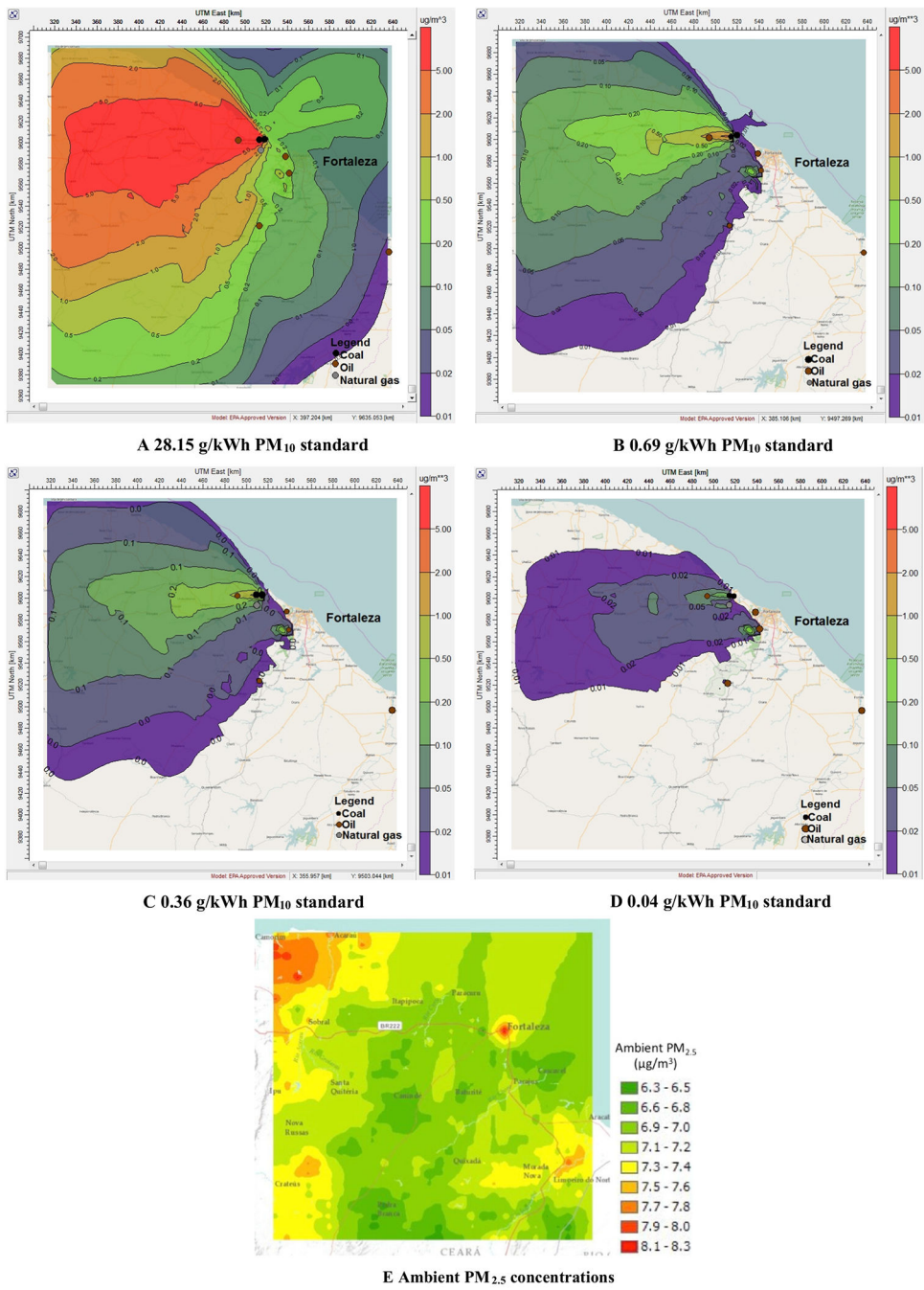


Fig. 4. Fortaleza study area average annual PM_{2.5} concentrations (µg/m³).

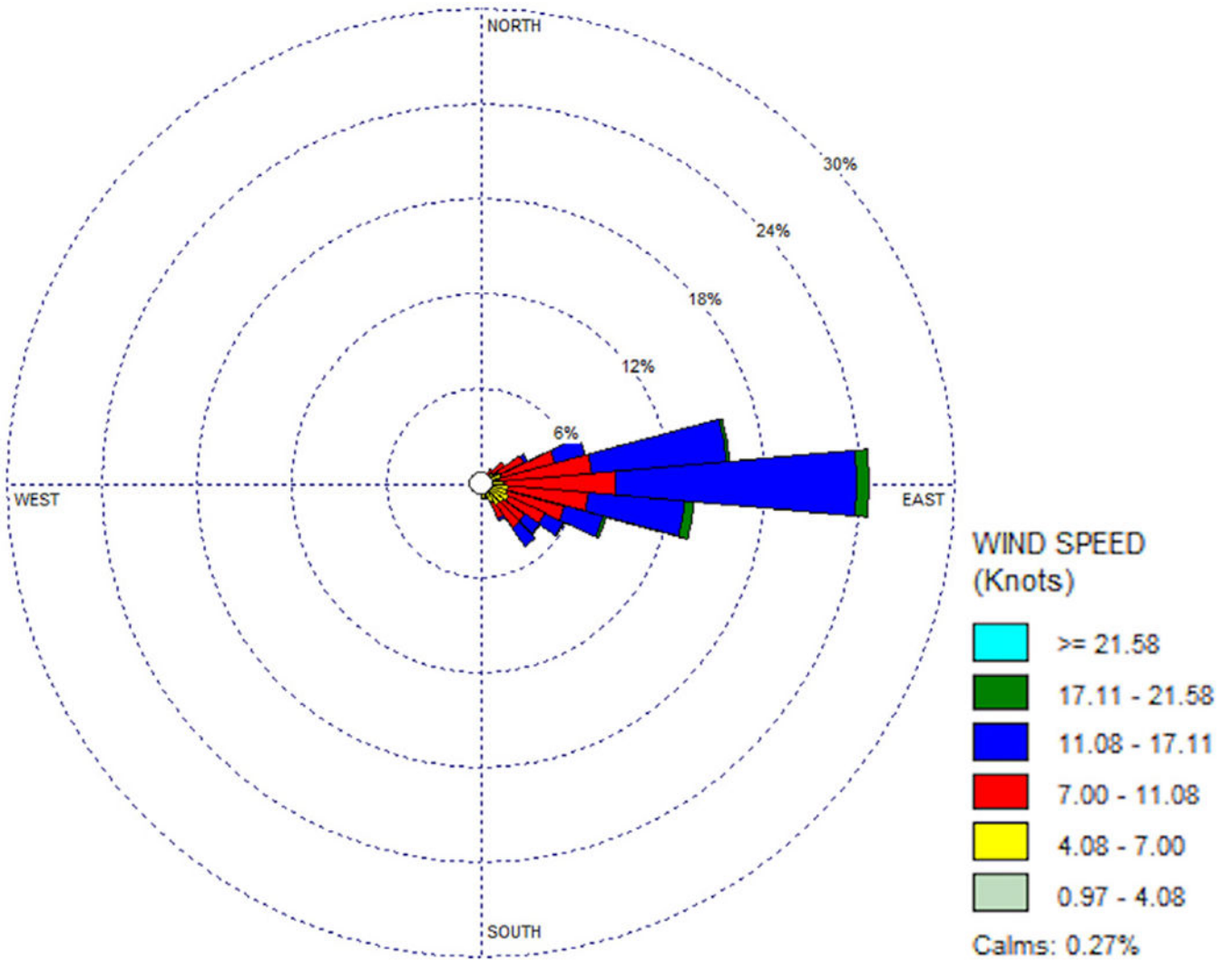


Fig. 5.
Year 2015 wind rose for the city of Fortaleza.

Table 1

Northeast Brazil electricity system capacity (2015).

Type	Number of generators	Total capacity (MW)	Percentage of system capacity
Renewable			
Wind	291	7650	25.9
Solar	52	1325	4.5
Hydro	11	14,721	49.8
Thermal			
Biomass	1	17	0.1
Natural gas	7	2094	7.1
Coal	2	1080	3.7
Oil	29	2684	9.1
Total	393	29,570	100.0

Source: Operador Nacional do Sistema Eletrico (ONS, n.d.).

Table 2

Selected C-R functions for mortality & hospital admissions.

Health endpoint	Health impact function authors	PM _{2.5} range (µg/m ³)	Location	Age range (years)
Mortality				
Cerebrovascular disease	Cohen et al. (2017)	1–300	Global	25–99
Chronic obstructive pulmonary disease	Cohen et al. (2017)	1–300	Global	30–99
Ischemic heart disease	Cohen et al. (2017)	1–300	Global	25–99
Lung cancer	Cohen et al. (2017)	1–300	Global	30–99
Lower respiratory infection	Cohen et al. (2017)	1–300	Global	30–99
All causes (infants)	Loomis et al. (1999)	4–85	Mexico City	0–1
Hospital admissions				
All cardiovascular	Moolgavkar (2000)	4–86	Los Angeles, CA	18–64
All cardiovascular	Zanobetti et al. (2009)	6.1–24	26 U.S. Communities	65–99
Asthma	Babin et al. (2007)	Not reported	Washington D.C.	0–17
Asthma	Slaughter et al. (2003)	5–60	Seattle, WA	18–64
Chronic lung disease (excl. asthma)	Moolgavkar (2000)	4–86	Los Angeles, CA	18–64
All respiratory	Zanobetti et al. (2009)	6.1–24	26 U.S. Communities	65–99

Note: "C-R" stands for "concentration-response".

Table 3Annual PM₁₀ emissions by standard (metric tons).

Emission source	PM ₁₀ Standard			
	28.15 g/kWh	0.69 g/kWh	0.36 g/kWh	0.04 g/kWh
Coal (tonne of PM ₁₀ /year)	246,663	6046	3154	351
Oil (tonne of PM ₁₀ /year)	1284	1284	1284	1284
Natural gas (tonne of PM ₁₀ /year)	732	732	732	732
Total (tonnes of PM ₁₀ /year)	248,679	8062	5170	2367

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Table 4

Air quality concentrations after dispersion ($PM_{2.5}$ $\mu\text{g}/\text{m}^3$).

PM_{10} standard	Average annual mean of all grid cells ($PM_{2.5}$ $\mu\text{g}/\text{m}^3$)	Maximum annual mean of all grid cells ($PM_{2.5}$ $\mu\text{g}/\text{m}^3$)	Maximum 24-hour mean of all grid cells ($PM_{2.5}$ $\mu\text{g}/\text{m}^3$)
28.15 g/kWh	2.01 [0.00, 91.7]	91.7	260
0.69 g/kWh	0.05 [0.00, 2.26]	2.26	6.38
0.36 g/kWh	0.03 [0.00, 1.18]	1.18	3.33
0.04 g/kWh	0.01 [0.00, 0.35]	0.35	2.17

Notes. 1) The average annual mean concentration is the average annual $PM_{2.5}$ concentration across all grid cells in our study area. The minimum and maximum values are presented in brackets. 2) The maximum annual mean concentration refers to the grid cell with the highest annual mean concentration. 3) The maximum 24-hour mean concentration represents the grid cell with the highest 24-hour concentration.

Table 5

Health benefits and control costs from tightening PM standards.

	Scenario 1: 28.15 → 0.69 g/kWh		Scenario 2: 0.69 → 0.36 g/kWh		Scenario 3: 0.36 → 0.04 g/kWh	
	Disease incidence (reduction/yr.)	Health benefits (million US\$2015/yr.)	Disease incidence (reduction/yr.)	Health benefits (million US\$2015/yr.)	Disease incidence (reduction/yr.)	Health benefits (million US\$2015/yr.)
Premature mortality, all causes	162	\$1104	3.6	\$24.4	4.1	\$28.0
Premature mortality, all causes (infants)	6	\$39	0.1	\$0.5	0.1	\$0.5
Additional hospital admissions, cardiovascular	10,829	\$90	131	\$1.1	129	\$1.1
Additional hospital admissions, respiratory	5428	\$31	66	\$0.4	65	\$0.4
Total		\$1264		\$26.4		\$30.0
		Scenario 1: 28.15 → 0.69 g/kWh		Scenario 2: 0.69 → 0.36 g/kWh		Scenario 3: 0.36 → 0.04 g/kWh
Emissions control costs (million US\$2015/yr.)		\$21.1		\$0.25		\$0.34
Health benefits/emissions control costs		60		103		89