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The energy-climate-health nexus in energy planning: A case study in Brazil

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ABSTRACT

Global greenhouse gas emissions from energy production were approximately 40% higher in 2017 than in 2000 (International Energy Agency, 2018), and ambient particulate matter – one of the byproducts from fossil fuel combustion of most concern for public health – is now the fifth largest contributor to global disease (Cohen et al., 2017). Achieving the climate targets of the Paris Agreement and the Sustainable Development Goals requires better accounting for climate and health costs in energy planning. This paper quantifies trade-offs between selected energy infrastructure, climate, and health costs when meeting future electricity demand by increasing the share of renewable energy, with a focus on variable renewable energy (VRE; here: wind and solar photovoltaic power). Using a spatially and temporally resolved approach, we analyzed three scenarios for year 2030 for Northeast Brazil, characterized by 30%, 45%, and 70% of VRE (the latter corresponds to 100% renewable energy). We find that accounting for the health impacts from electricity generation is sufficient to economically justify deep decarbonization of Northeast Brazil's power sector. Full decarbonization is economically justified when the carbon price exceeds \$20/tonne CO_2, which is less than Brazil's country-level social cost of carbon and only 4.8% of the global social cost of carbon. Our study shows that regional climate and health costs from electricity generation alone can be greater than the additional infrastructure costs of decarbonization. Our results highlight how systematically accounting for health and climate costs in energy planning would economically justify the decarbonization of energy systems.

1. Introduction

The soaring worldwide demand for energy is creating unprecedented energy, climate, and health challenges. From 2017 and 2040, world energy demand is forecasted to grow by 25% and electricity demand is forecasted to increase by 64–90% depending on the pace of electrification [1]. Despite numerous warnings about the perils of global climate change, global energy-related CO_2 emissions were 40% higher in 2017 than in 2000 [2], and the climate actions currently proposed by all countries would slightly increase annual global CO_2 emissions by 2030 instead of cutting them in half as required to meet the Paris Agreement goals [3]. And while ambient particulate matter (PM) concentrations decreased globally between 1990 and 2015, the annual number of deaths from exposure to ambient PM increased from 3.5 million to 4.2 million due to population growth, making ambient PM the fifth largest contributor to global disease in 2015 [4]. Although the Covid-19 pandemic is expected to decrease global demand for energy by 6% and global CO_2 emissions by 8% in 2020, its impacts are likely to wane over the next few years [5].

Many studies have concluded that meeting the increasing energy demand, while decreasing greenhouse gas (GHG) and air pollutant emissions, requires decarbonizing the electricity sector jointly with electrifying at least parts of the transportation and industrial sectors [6–10]. This will require increasing substantially the generation of electricity from renewable sources. We do not consider carbon capture and storage (CCS) here because it suffers from relatively low net capture rates and it does not decrease air pollution and its health impacts, so its social costs are higher than those of wind power, for example [11]. We also do not consider nuclear energy for two reasons: first, social and political opposition to its adoption is substantial [12,13], and second, nuclear energy is not economically attractive in Brazil [14].

Since the potential to generate electricity from hydropower, geothermal, bioenergy, wave and tidal resources is limited and/or

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Table of abbreviations

ANEEL	Agência Nacional de Energia Elétrica
CO_2	Carbon dioxide
C-R	Concentration response (function)
CCS	Carbon capture and storage
CSCC	Country-level social cost of carbon
CSP	Concentrated solar power
GDPPC	Gross domestic product per capita
GHG	Greenhouse gas
GSCC	Global social cost of carbon
GW	Gigawatt (10^9 W)
HVDC	High-voltage direct current
IER	Integrated exposure-response
kW	Kilowatt (10^3 W)
MW	Megawatt (10^6 W)
MWh	Megawatt hour (10^6 W of electricity used continuously for 1 h)
NE	Northeast
NO_x	Nitrogen oxides
O_3	Ozone
PM (PM_x)	Particulate matter (PM with a diameter $\leq x$ micrometers [1 μm = 10^{-6} m])
PPP	Purchasing power parity
PV	Photovoltaic
RE	Renewable energy
SIN	Sistema Interligado Nacional
VOCs	Volatile organic compounds
VSL	Value of a statistical life
VRE	Variable renewable energy

expensive in many regions [15], this leaves wind and solar resources to supply part of new electricity demand in regions where these resources are available. This is especially the case in Northeast (NE) Brazil [16], the area we analyze here. One drawback of wind and solar photovoltaic power plants, however, is that their electricity generation varies based on fluctuating wind speed and solar irradiation patterns, hence their variable renewable energy (VRE) label. While VRE relies on domestically available resources and does not emit operational GHG or air pollutants, high levels of VRE create new concerns about grid reliability for electricity grid operators [17].

Fully implementing the Paris Agreement and the Sustainable Development Goals would likely fulfill the rising demand for energy, while decreasing emissions of greenhouse gases (GHGs) and of harmful pollutants such as particulate matter (PM), and keep the increase in global average temperature below 2.0 °C above pre-industrial levels. Some countries are developing plans to achieve these energy and climate goals, such as the National Energy and Climate Plans that all EU Member States are mandated to develop under the "Regulation on the governance of the energy union and climate action (EU)2018/19" set forth by the European Commission [18]. While decarbonizing energy systems requires substantial infrastructure investments, it also yields large decreases in climate and health costs [19]. This trade-off needs to be quantified for conducting sound public policy. We call "energy-climate-health nexus" the interactions between energy production, climate and health impacts.

In this context, our study presents a widely applicable, spatially and temporally-resolved approach to explore the energy-climate-health nexus in energy planning with an application to NE Brazil. Specifically, we explore meeting future electricity demand by increasing the share of renewable energy, and we monetize the trade-offs that arise between infrastructure capital and operational expenses on the one hand, and climate and health impacts on the other hand. Our findings highlight the importance of accounting for health and climate costs in energy planning.

2. Review of previous work

Incorporating high levels of VRE into electric grids is an active research area, as researchers still disagree about the time horizon needed to supply all electricity demand with 100% renewable energy (RE). For example, Jacobson et al. [20] found that an interconnected electricity grid in the United States based only on solar, water, and wind energy could reliably and affordably fulfill energy demand by the middle of the 21st century. Clack et al. [21], however, argued that electricity grids may not be able to handle the voltage and frequency requirements of high VRE systems with current technologies, and that deploying new electricity storage technologies at commercial scale might require more than three decades.

Several other recent studies have also assessed the feasibility of 100% RE systems by the 2030 to 2050 time horizon. Interconnected grid studies in the European Union [22,23], Eurasia [24], Denmark [25], the Americas [26], Brazil [27,28], Northeast Asia [29], Southeast Asia and the Pacific Rim [30] have found that 100% RE systems are technically feasible if electricity grids are interconnected and if a portfolio of dispatchable RE and storage options are deployed. Most of these studies argue that producing all electricity from RE would be less costly than relying on nuclear energy and fossil fuels with carbon capture and storage alternatives. Using arguments based on science and engineering, Diesendorf and Elliston [31] refuted the main myths about 100% RE power systems with high levels of VRE, and showed that those systems can readily meet the key requirements of reliability, security, and affordability. However, except for Jacobson et al. [19], the studies above do not monetize health impacts or carbon emissions.

Recent studies have explored different dimensions of the energy-climate-health nexus. Scovronick et al. assessed health co-benefits relating to global climate policy [32]. Several studies, most notably Buonocore et al. [33], have compared climate and health benefits related to specific technologies to highlight the importance of site-specific information for estimating public health and climate benefits of renewable energy projects. More recently, Buonocore et al. [34] analyzed the climate and health benefits of deploying varying capacities of wind and solar generators across the US.

In this paper, to explore trade-offs between the cost and the benefits of decarbonization with high penetrations of VRE, we used a systems approach to simulate up to a 100% RE power matrix and estimate selected infrastructure, climate, and health costs. In addition, we looked for the break-even carbon price where the sum of annualized infrastructure, annual climate, and annual health costs are equivalent between two scenarios characterized by different levels of VRE (corresponding to different levels of decarbonization), and above which it would be economically justified to opt for the scenario with a greater level of decarbonization.

3. Study area and scope

3.1. Study area

Brazil, the largest economy in Latin America, is ideal to study decarbonization because of its large potential for hydroelectric, wind, and solar power [16], and for its growing demand for electricity (~4.5% annually for the last 20 years [35]).

Brazil's electricity transmission system (the Sistema Interligado Nacional, or SIN) consists of five interconnected regions (North, Northeast, Midwest, South, and Southeast) and an isolated Amazon system [36]. To keep this study manageable, we focused on NE Brazil because of its high VRE potential [16,37] and the availability of key data thanks to two public national energy infrastructure expansion plans: 2013–2023 [36] and 2022–2027 [38]. Fig. 1 displays the five interconnected regions (N, NE, MW, S, SE) as well as the main nodes of the Brazilian power system. The interconnection of the NE subsystem with the rest of SIN is captured by two links: one with the Southeast/Midwest region, and one with the Imperatriz substation.

Fig. 1 depicts system boundaries for Northeast Brazil electricity imports and exports. The main nodes in the Brazilian power system are NE (Northeast); SE/MW (Southeast/Midwest); IMPE (Imperatriz); N (North); XIN (Xingó); TP (Tapajós); BM (Belo Monte); MAN/AP/BV (Manaus/Amapá/Boa Vista); AC/RO (Acre/Rondônia); IT (Itaipu); IV (Ivaiporã); and S (South). Source: Ministério de Minas e Energia [36].

NE Brazil roughly fits in a 1200 km (width) by 1500 km (length) rectangle. Since puff modeling is less reliable for distances over 350 km [39], we created three air quality modeling regions measuring 320 km × 320 km around NE Brazil's largest cities of Recife, Salvador and Fortaleza (Fig. 2) Their metropolitan populations ranged between 3.5 and 3.9 million each in 2015, and represented approximately one fifth of the population in NE Brazil [40]. Of the 39 thermal power plants in NE Brazil in 2015, 28 of are within the Recife, Salvador and Fortaleza air quality modeling regions, and over 90% of power plant PM emissions in our simulations occur in these regions. Emissions outside these regions were not considered, including from imports, which further reinforces the conservative nature of our health impact assessments.

3.2. Scope

Our main goal in this paper is to estimate infrastructure, climate, and health costs for NE Brazil in 2030 for different levels of VRE to analyze the energy-climate-health nexus, and in particular the carbon prices that economically justify transitioning to higher levels of VRE.

We selected the 2015–2030 period because many of the data we need are available only up to 2030. To supply the NE Brazil electricity demand in 2030 forecasted by Torrini et al. [42], we extended to 2030 the installed capacity of Brazil's electricity grid based on the 2013–2023 and 2022–2027 electricity grid expansion plans [36,38]. Next, we defined three scenarios for year 2030 characterized by different VRE levels: 30%, 45%, and 70% (see Table 1). The 2030 30% VRE is our baseline, as this VRE penetration was achieved in 2015 and is the target stated in the 2022–2027 electricity grid expansion plan [38]. The 45% VRE scenario is a midline case, while the 70% VRE scenario corresponds to 100% RE. Note that as of 2015, RE including hydro made up ~80% of Brazil's electricity infrastructure installed capacity and ~60% of generation [43]. Extending our analysis beyond 2030 would entail greater uncertainty about generation and storage technologies, infrastructure costs, population growth, energy demand, and meteorological conditions under global climate change.

4. Methods

To assess infrastructure, climate, and health costs of decarbonization electricity production for various levels of VRE in NE Brazil, we applied an integrated, spatial-temporal approach [44] that combines a power system dispatch optimization tool (PLEXOS®) [45], with an air

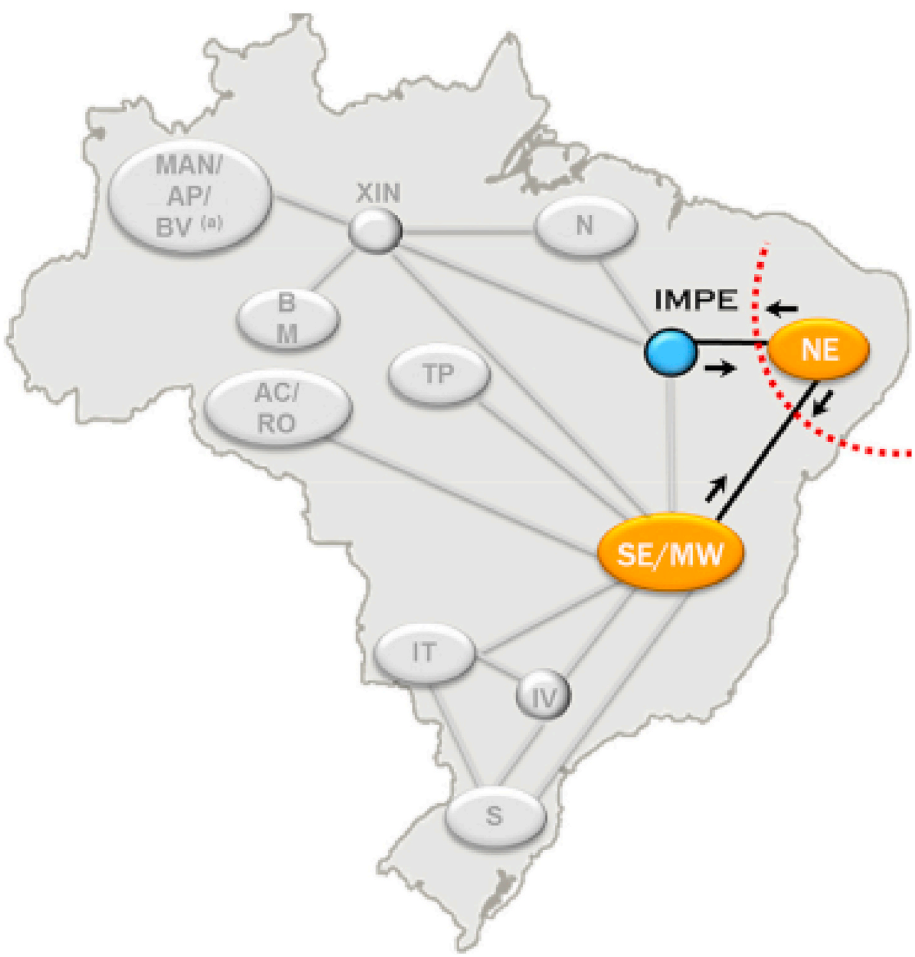


Fig. 1. Brazilian electricity system.

Fig. 2. Study areas for emission dispersion and health impacts, Source of background map: [41].

dispersion model (CAPUFF View) [39] (both of which generated hourly data for an entire year), and a health outcome assessment tool (BenMAP) [46]. We summarize each component of our methodology in turn.

4.1. Modeling NE Brazil's electric system

Modeling electricity grid interactions at the power plant level and calculating emissions, in time and space, is necessary here for analyzing trade-offs between infrastructure, climate, and health costs. We built a spatially and temporally resolved electricity dispatch model for NE Brazil using PLEXOS®. Recent studies have used PLEXOS® to model the energy-water-climate nexus [47], large-scale renewable integration assessment [48], and electricity grid impacts of high penetrations of wind energy in Brazil [49]. PLEXOS® calculates the optimal dispatch of a power system (unit commitment problem) in time and space to match system load at the lowest variable cost subject to economic and operational constraints.

4.1.1. NE Brazil's electric system data, key assumptions, and model calibration

Data on the entire NE Brazil electric system, including generators, fuels, emissions, storage, and reserves were collected in collaboration with the Center for Energy and Environmental Economics at the Universidade Federal do Rio de Janeiro from publicly available sources [43, 50]. Key information is provided in Tables A1-A5 in the Appendix.

The maximum potential for hydroelectricity in NE Brazil was assumed to be 26,300 MW. It was obtained by summing the hydroelectric potential of each hydrographic basin in the region, reported by Agência Nacional de Energia Elétrica (ANEEL), Brazil's National Electric Energy Agency (Table A1) [51]. Like Gils et al. [28], we assumed that pump turbines were installed at all hydro stations with reservoirs, which have an aggregate capacity of 7215 MW, for additional flexibility and storage.

The maximum potential for onshore wind and solar PV energy in NE Brazil were set at 71 GW and 1000 GW, respectively, as in Gils et al. [28], who used these renewable energy potentials in their investigation of the 100% renewable energy case for Brazil in 2050. Our scenarios do not include offshore wind generation because that option is not included in Brazil's 2013–2023 and 2022–2027 electricity expansion plans [36, 38]. Following Soria et al. [37], who generated location specific hourly generation profiles for wind and solar PV power plants in NE Brazil, we simulated eight wind hotspots and three solar hotspots in locations ideal for wind and solar energy production in NE Brazil (Table A2). Using multiple hotspots captures the geographic diversity of wind and solar generation patterns, which provides better assessments of the load balancing requirements as VRE levels increase.

The only storage option utilized was pumped hydro storage at hydro stations because we restricted ourselves to technologies that were

Table 1
Northeast Brazil electricity grid in the base year and in 2030 for three scenarios.

Type	Year 2015	Year 2030 electricity grid scenarios		
	Baseline♣	30% VRE◆	45% VRE♠	70% VRE♥
Share of installed capacity				
Wind	25.9%	25.2%	39.0%	60.1%
Solar PV	4.5%	4.4%	6.8%	10.4%
Hydro	49.8%	42.0%	33.1%	29.5%
Biomass	0.1%	0.1%	0.1%	0.0%
Natural gas	7.1%	15.9%	16.3%	0.0%
Coal	3.7%	3.6%	1.4%	0.0%
Oil	9.1%	8.8%	3.4%	0.0%
Total installed Capacity (MW)	29,570 MW	60,783 MW	78,478 MW	88,910 MW
VRE (% of system capacity)	30.4%	29.6%	45.8%	70.5%
Total RE (% of system capacity)	80%	72%	79%	100%

For the year 2015 baseline, there is no pumped hydro capacity. For each 2030 electricity grid scenario, total pumped hydro capacity is 7,215 MW, from 9 sites. RE denotes renewable energy. VRE refers to variable renewable energy (85% wind and 15% solar PV by installed capacity). ♣: 2015 base year electricity grid infrastructure; ◆: scenario with ~30% VRE, which corresponds to a business-as usual situation similar to Brazil's 2013-2023 and 2022-2027 electricity expansion plans; ♠: scenario with ~45% VRE; ♥: scenario with ~70% VRE (it corresponds to 100% RE).

already operational in Brazil during our study period or that were considered in Brazil's 2013–2023 and 2022–2027 electricity expansion plans [36,38]. Additional flexibility could be provided by a number of alternatives, including high-voltage direct current (HVDC) transmission lines, dispatchable renewable energy such as concentrated solar power (CSP) and biomass, or energy storage via batteries and power-to-gas [27]. For further power system flexibility analysis, see Fichter et al. [52] who performed a detailed assessment of the role of solar CSP with thermal energy storage in NE Brazil.

Transmission system data were obtained from Miranda et al. [17], who investigated the effects of detailed transmission constraints using a long-term integrated assessment tool for Brazil. In our simplified model of NE Brazil's electric system, all transmission line voltage constraints were enforced, although we did not model the finer distribution scale impacts. For electricity infrastructure and operating cost data for Brazil, we relied on Fichter et al. [52], and performed a sensitivity analysis using costs from Barbosa et al. [27] (see Section 5.4). We selected the 2010 dataset from Fichter et al. [52] because it is congruent with data from recent studies [53] and with official expansion plans [36], while Barbosa et al. [27] make assumptions about the global learning rate and economies of scale for RE that substantially lower RE capital costs. Capital expenditures were annualized using a 7% discount rate, which is the average cost of capital for renewable energy projects in Brazil [54], and both capital costs (US$/kW) and fixed operating costs (US$/kW) were multiplied by the technology specific capacity in each of the 2030 scenarios. Variable operating costs were estimated by multiplying the actual generation in each 2030 scenario by variable operating costs per unit of generation. We converted costs in Euros to US$ using the average exchange rate in 2015 (costs are presented in Table A3).

We used the monthly average marginal cost of operation from CCEE [55], Brazil's electricity trading body, to monetize import and export requirements. We chose this simple approach because NE Brazil is part of the Brazilian national power system, which does not currently have import/export contracts. We were unable to monetize the infrastructure cost of the transmission system expansion because this would require detailed modeling of unit commitment and dispatch for the entire Brazilian power system, which is beyond the scope of this study. However, we checked that the forecasted transmission capacity between regions by 2030 was not exceeded based on data from Gils et al. [28] and Miranda et al. [17].

Finally, we collected the actual 2015 load profile from the Agência Nacional de Energia Electrica, which is Brazil's national power system operator [50]. We used that information to calibrate our model by simulating electricity dispatch and unit commitment in the NE Brazil electric system for the entire 2015 year for all 393 generators centrally dispatched by Brazil's national power system operator (Table A4) [50]. We then adjusted our model by changing the maximum energy per month dispatch constraint on hydroelectric power plants with reservoirs until the generation from our simulations matched actual generation data [43]. Total generation in our final simulations was within 0.6% of the actual load profile, and hydroelectric generation was within 3.2% of the actual generation.

4.1.2. Scenarios

Next, we designed three scenarios for 2030. They are characterized by their installed capacity percentage of VRE: 30%, 45% and 70%. The 30% VRE scenario follows similar trends as the 2013–2023 and 2022–2027 power system expansion plans, which specify renewable energy targets by installed capacity percentages [36,38]. The 45% VRE scenario represents a midline scenario, and the last scenario corresponds to 100% RE, which in our simulations is achieved with 70% VRE.

We derived an hourly 2030 load profile for NE Brazil from the actual hourly load profile for 2015 [50], based on a forecasted average annual electricity demand increase of 4.77% by Torrini et al. [42]. As a result, annual electricity demand would increase by 121%, from 88,059 MWh in 2015 to 194,562 MWh in 2030. In the 30% and 45% VRE scenarios, we added future power plants approved by ANEEL up to year 2022 [43]. None of the thermal generators operational in 2015 were decommissioned because the earliest planned retirement year of these generators is 2036. Technical properties specific to each generator incorporated in our model include maximum capacity, heat rate, minimum stable level, ramp rates, minimum uptime and downtime, start time and emissions rates. We assumed that new generators are in the same location and have the same characteristics as existing generators.

In the 30% VRE scenario, which is intended to represent business as usual, the 2015 installed capacity of wind, solar PV, coal, and oil power plants doubled, similar to the 2013–2023 and 2022–2027 energy plans [36,38]. In the 45% VRE scenario, no new coal and oil generators were added beyond those already installed in 2015, and the 2015 installed capacity of wind and solar energy was quadrupled. In both scenarios, hydroelectric capacity was increased to its maximum technical potential and natural gas power plants were added until load and generation were sufficiently balanced.

In the 70% VRE scenario, all thermal generators were decommissioned. Hydroelectricity was increased to its maximum technical potential, and wind and solar generators were added, keeping the proportion of wind (85%) and solar (15%) by installed capacity the same as in the base year, until the storage constraints limiting the ability to temporally shift generation were met. Table 1 shows the percentage of installed capacity by energy source and Table A4 displays the installed capacity and the number of generators by energy source in each scenario.

4.1.3. Year 2030 scenario simulations

Following Soria et al. [37], we simulated the location specific hourly generation of wind and solar photovoltaic power plants. Hydroelectric dispatch was constrained by water reservoir initial and final fill levels according to the historical monthly dispatch data. Initial reservoir levels were set at their January 1, 2015 values, and final reservoir levels were constrained to be equal or greater than those of December 31, 2015. The maximum dispatchable energy for each hydroelectric plant in 2030 was constrained based on historical monthly hydroelectric dispatch. Because precipitation in NE Brazil has been forecasted to continue decreasing [56], we also simulated the 45% VRE scenario under dry year conditions, where water reservoir fill levels were constrained by the difference between the average annual precipitation and precipitation in the driest year in the NE Brazil water basin since 1983 [56]. Dry year conditions lead to lower hydroelectric generation, requiring increased generation and higher air pollutant and CO_2 emissions from thermal power plants.

Hourly PM_{10} and CO_2 emissions were simulated in PLEXOS® for each power plant based on the actual dispatch of each power plant and technology specific emission standards shown in Table A5 [57,58]. PM_{10} emissions were converted to $PM_{2.5}$ emissions using the ambient ratio method [59]. As the ratio of $PM_{2.5}$ to PM_{10} varies by fuel source, we first averaged all reported $PM_{2.5}$ to PM_{10} emissions (by mass) for coal, oil, and natural gas generation in the United States (Brazilian data were unavailable), and then weighted the ratio based on each fuel source's contribution to emissions in the NE Brazil electric grid, resulting in a $PM_{2.5}$ to PM_{10} ratio of 0.775.

To validate simulations for the 2030 scenarios, we ensured that no constraints were violated, and checked that generation patterns are similar to historical patterns. We also verified that generation and emissions are congruent.

4.2. Climate costs

To estimate the global climate costs caused by the NE Brazil electricity system, we multiplied the NE Brazil electricity system annual CO_2 emissions by the median global social cost of carbon (GSCC) of $417/tonne. To estimate the domestic climate costs specific to Brazil, we multiplied the NE Brazil electricity system annual CO_2 emissions by Brazil's median country-level cost of carbon (CSCC) of $24/tonne. The CSCC estimates the amount of marginal damage expected to occur in an individual country due to emitting an additional tonne of CO_2, while the GSCC is the sum of CSCC values for all countries where data are available. To the best of our knowledge, only Ricke et al. [60] estimated both CSCC and GSCC values, and thus we used both of their CSCC and GSCC estimates for consistency.

We also calculated the cost of a tonne of CO_2 that would equalize the sum of infrastructure, health, and climate costs between scenarios. These break-even points are the minimum social costs of carbon that would economically justify moving to a higher VRE level.

4.3. Health modeling

4.3.1. PM dispersion

We dispersed hourly primary PM emissions from each fossil fuel power plant in NE Brazil using CALPUFF View™ [39], which is widely used in atmospheric dispersion modeling. We modeled only primary PM emissions because the emissions inventories required for modeling secondary pollutant formation, including ozone (O_3), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) are not available for NE Brazil (Sogabe, M.N., Environmental Company of the State of Sao Paulo, personal communication, 2018). To explore the potential impact of secondary PM on our results, we conducted a sensitivity analysis using ambient air pollutant concentrations of O_3, NO_x and VOCs equivalent to those in Southern Texas, which likely exceed concentrations of these pollutants in NE Brazil, thus giving us an upper bound for secondary PM. Results of this analysis are discussed in Section 5.4.

As mentioned in Subsection 3.1, we created three air quality modeling regions measuring 320 km × 320 km around NE Brazil's largest cities of Recife, Salvador and Fortaleza because there is less certainty with puff modeling in distances over 350 km [39]. Of the 39 thermal power plants in NE Brazil in 2015, 28 are within the Recife, Salvador and Fortaleza air quality modeling regions and over 90% of the NE Brazil electric grid emissions in our simulations occur in these regions (see Fig. 2). Emissions outside these regions were not considered, including from imports, which further reinforces the conservative nature of our health impact results.

Meteorological data are an essential input in dispersion analyses. For each of our three air quality modeling regions, we asked Lakes Environmental Inc. to develop hourly 3D meteorological Weather and Research Forecasting (WRF) files for year 2015. These data were used in all of our scenarios so they would reflect only the impact of higher VRE penetration and not different meteorological conditions. The exception is the 45% VRE scenario under dry year conditions, which was created to explore the potential impacts of climatic change. For the latter, Lakes Environmental Inc. generated instead WRF files for year 2012, the driest year in the NE Brazil water basin since 1983 [56]. Meteorological files include surface 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. In addition, we adjusted modeling parameters in CALPUFF View™ to reflect the terrain and the meteorology in NE Brazil, including plume elements, temperature gradients, and radius of terrain influence.

The gridded air quality concentrations output by CALPUFF were checked for spatial and temporal congruency with power plant emissions. Moreover, the wind roses for each study area were compared against historical data. Finally, hourly, daily, and annual concentration averages and maxima were compared between grid cells and between simulations.

4.3.2. Assessing health impacts

After dispersing hourly primary PM emissions from the power plants in NE Brazil, we mapped air quality concentrations to human health impacts using the EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) [46], which is widely used in health impacts modeling. BenMAP calculates air quality differences between two scenarios, before overlaying these differences on population characteristics to calculate changes in disease incidence for selected health outcomes. While a number of air pollution health impact assessment tools are available, we chose BenMAP for its compatibility with the latest integrated exposure-response (IER) model [4] and for its flexibility, which allowed us to use the highest resolution available for each dataset as well as updated monetary valuation metrics specific to Brazil.

Evaluating health impacts requires several gridded datasets for each study area: baseline air quality concentrations, air quality concentration changes for each scenario, population data and baseline disease incidence data. Our baseline $PM_{2.5}$ concentrations come from the 2013 Global Burden of Disease study [61]. To match our air quality modeling grids, we increased their original 10 km × 10 km resolution to a 5.4 km × 5.4 km resolution using the inverse distance weighting method because it is preferred to Thiessen polygons and kriging for air quality applications [62]. Our gridded population data for 2015 were sourced from the United Nations Socioeconomic Data and Applications Center [63]. We used population growth predictions for each age group in Brazil from 2015 to 2030 [64] to derive a gridded and age-stratified population dataset for 2030.

To estimate health impacts, we chose the latest version of the IER model because it performs better than other exposure-response functions [65]. The IER model averages relative risk functions from different regions around the globe to estimate the full exposure range of PM for each cause of PM-related mortality in adults. We did not find $PM_{2.5}$-related hospital admissions concentration-response (C-R) functions for Latin America, so we relied on prominent US studies [66–69]. This gave us an annual number of cases for various health outcomes in each of our three study areas, for each of our scenarios.

4.3.3. Health costs

To monetize premature mortality from ambient PM exposure, we applied the value of a statistical life (VSL) method [70]. First, we calculated the US VSL for 2030 from

$$US\ VSL_{2030} = US\ VSL_{2026} * \left(\frac{CPI\ US_{2030}}{CPI\ US_{2026}}\right) \tag{1}$$

using data forecasted by the US EPA [71]: the 2026 US VSL (US VSL_{2026} = \$10.4 million) in 2015 US\$ and the ratio consumer price indexes (CPI US_{2030}/CPI US_{2026} = 1.0626). The result is US VSL_{2030} = \$11.05 million in 2015 US\$. Following [70], we then calculated a VSL for Brazil for year 2030 in 2015 US\$, using Eq. (2):

$$BR\ VSL_{2030} = US\ VSL_{2030} * \left(\frac{BR\ GDPPC_{2015}}{US\ GDPPC_{2015}}\right)^{\eta} * PPP_{BR,\ 2015} \tag{2}$$

In 2015, the Brazil and US gross domestic product per capita (GDPPC) were respectively \$15,615 and \$56,207, and the purchasing power parity (PPP) for Brazil compared to the US (i.e., the coefficient that adjusts the purchasing power in Brazil compared to the US) was 1.9 [35]. For the elasticity of income with respect to the willingness to pay to avoid adverse health effects, which is denoted by η in Equation (2), we adopted the OECD [72] recommended value of $\eta = 0.8$. The resulting 2030 VSL for Brazil is then \$7,536,210 in 2015 US\$.

Finally, to value various forms of morbidity we relied on the cost-of-illness method. We applied this method using average hospitalization cost in Brazil for all respiratory and all cardiovascular hospital admissions for the health endpoints we considered [73].

5. Results

Table 2 summarizes how infrastructure, climate, and health costs vary between the three 2030 scenarios. The sum of infrastructure, climate, and health costs does not change drastically as VRE levels increase when carbon is priced at or near the CSCC. However, when carbon is priced at the GSCC, the sum of infrastructure, climate, and health costs decreases sharply as VRE levels increase.

Fig. 3 presents the sum of infrastructure, climate, and health trade-off costs for each scenario as a function of the price of carbon. The sum of costs for the 45% VRE scenario is less than the 30% VRE scenario for all carbon prices, which shows that accounting for health costs alone is sufficient for economically justifying moving from 30% VRE to 45% VRE. The sum of costs for the 45% VRE and 70% VRE scenarios are equivalent for the break-even value of ~\$20/tonne of CO_2 (the exact value is \$19.83). which is ~\$4/tonne less than Brazil's CSCC of \$24/tonne. Above \$20/tonne of CO_2, the 70% VRE scenario is economically preferable to the 45% VRE scenario.

5.1. Electricity system costs

We optimized hourly power system unit commitment based on marginal dispatch cost for an entire year for each scenario using PLEXOS®. The annualized infrastructure costs are US\$17.83 billion for the 30% VRE scenario, US\$18.87 billion for the 45% VRE scenario and US\$19.49 billion for the 70% VRE scenario (Table 2).

Table 3 provides an overview of system capacity and load balancing requirements for our scenarios. As VRE levels increase, so do total system capacity, storage and import/export requirements. The VRE energy fraction is the percentage of VRE energy used to meet load (electricity plus pumped hydro storage), which increases substantially from the 30% VRE to the 45% VRE scenario because there is sufficient pumped hydroelectric capacity to store energy when generation is greater than load. In the 70% VRE scenario, however, there is not sufficient pumped hydroelectric storage capacity to store all of the energy when generation is greater than load, which limits the VRE energy fraction and results in higher import and export requirements.

While almost all load (99.98%) can be served from the NE Brazil subsystem in the 30% and 45% VRE scenarios, the 70% VRE scenario requires 12.6% of load to be imported from, and 23.0% of generation to be exported to the North and Southeast regions. These two regions have higher hydroelectric generation as well as additional technical and economic potential to deploy seasonal pumped hydropower storage, allowing for greater dispatch and system balancing flexibility [28,38]. To better understand the most extreme generation patterns, Fig. 4 shows hourly generation by technology type for the week with the highest electricity imports for each scenario. When generation is less than the total system load (plotted in purple, including electrical and pumped hydro storage load), importing electricity from other regions (shown in red) is required. When generation is greater than load, electricity must be exported or curtailed.

Natural gas and oil generators are dispatched to make up the difference between load and RE generation with a small amount of imported electricity (shown in red) in the 30% and 45% VRE scenarios, while the 70% VRE scenario relies on imports and exports. Large spikes in VRE generation show that increasing VRE levels in the 70% VRE scenario will only minimally contribute to meeting load because of limited energy storage capacity, so substantial imports and exports are required. Alternatively, instead of interconnections with other regions, additional load balancing flexibility could be provided by other means, such as dispatchable RE like CSP with thermal energy storage and bioenergy, energy storage via batteries and power-to-gas, or sector integration [74]. For additional analyses, see Fichter et al. [52], who performed a detailed assessment of the role of CSP with thermal energy storage in NE Brazil.

5.2. Climate costs

The annualized country-level climate costs and global climate costs

Table 2
Electricity infrastructure, climate and health trade-off costs.1

Cost (billions of 2015 US\$)	Year 2030 electricity grid scenarios 30% VRE	45% VRE	70% VRE
IC: Annualized infrastructure costs	\$17.83 billion	\$18.87 billion	\$19.49 billion
HC: Annual health costs	\$1.38 billion	\$0.14 billion	\$0.00 billion
CE: Annual CO_2 emissions (tonnes)	48.4 million	24.2 million	0.00 million
Sum of costs for a CO_2 price of p=\$20/tonne	**\$20.18 billion**	**\$19.49 billion**	**\$19.49 billion**
Sum of costs for a GSCC CO_2 price of p=\$417/tonne	**\$39.40 billion**	**\$29.10 billion**	**\$19.49 billion**

Sum of costs: IC + HC + p*CE

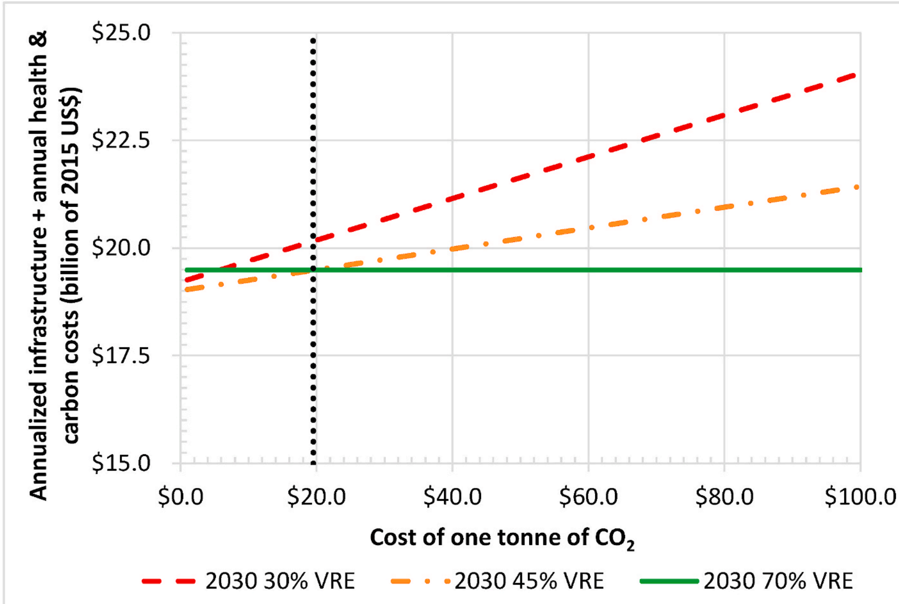


Fig. 3. Sum of annualized electricity infrastructure, carbon, and health costs vs. cost of carbon.

Table 3
System capacity and load balancing requirements.

Capacity and load balancing	Year 2030 electricity grid scenarios		
	30% VRE	45% VRE	70% VRE
System capacity (MW)	60,783 MW	78,478 MW	88,910 MW
Total RE installed capacity (% of system capacity)[a]	72%	79%	100%
VRE installed capacity (% of system capacity)[a]	30%	45%	70%
VRE energy fraction (% of system load)	22.2%	38.9%	48.4%
Pump storage load (GWh)	10,482 GWh	15,688 GWh	17,850 GWh
Imports from other regions (% of system load)	0.02%	0.02%	12.6%
Exports to other regions (% of system generation)	0.0%	4.6%	23.0%

[a] rounded to the nearest 1 percent.

related to power plant CO_2 emissions from NE Brazil's power system are presented in Table 4. Under the 70% VRE, there are no CO_2 emissions because all the energy produced comes from renewable sources and electricity imports are assumed to come from RE, so climate costs are $0. Table 4 also presents results for a dry year (as a sensitivity test) for the 45% VRE scenario. While global climate costs for the 45% VRE scenario increase by 35.7% under dry year conditions ([$13.69-$10.09]/$10.09), they are still 32.2% less than in the 30% VRE scenario. See 5.4 for details.

The country-level and global climate costs caused by NE Brazil's power system are relatively low compared to regions with similar energy demand because Brazil has much higher levels of RE than most countries, with RE making up ~80% of installed capacity and ~60% of electricity generation in 2015 [43]. Even in this case, the global climate costs are greater than infrastructure and health costs combined in the 30% VRE scenario.

5.3. Health costs

5.3.1. PM concentrations

The first step in estimating health costs from $PM_{2.5}$ exposure is simulating the dispersion of power plant emissions and estimating the resulting air quality concentrations of $PM_{2.5}$.

Panels A–C of Fig. 5 illustrate the annual mean $PM_{2.5}$ concentrations due to power plant emissions in the 30% and 45% VRE scenarios for Fortaleza, Recife, and Salvador, the three largest cities of NE Brazil. As expected, the $PM_{2.5}$ emissions disperse westerly according to the predominant wind direction (which blow inland). Furthermore, annual mean $PM_{2.5}$ concentrations decrease as VRE levels increase. Table A6 shows the peak annual mean $PM_{2.5}$ concentration due to power plant emissions for each scenario, including dry year conditions. While $PM_{2.5}$ concentrations increase under dry year conditions, they are still substantially less in the 45% VRE dry year scenario than the 30% VRE scenario. Note that there are no $PM_{2.5}$ emissions in the 70% VRE scenario because it involves no fossil fuel generator.

5.3.2. Health outcomes

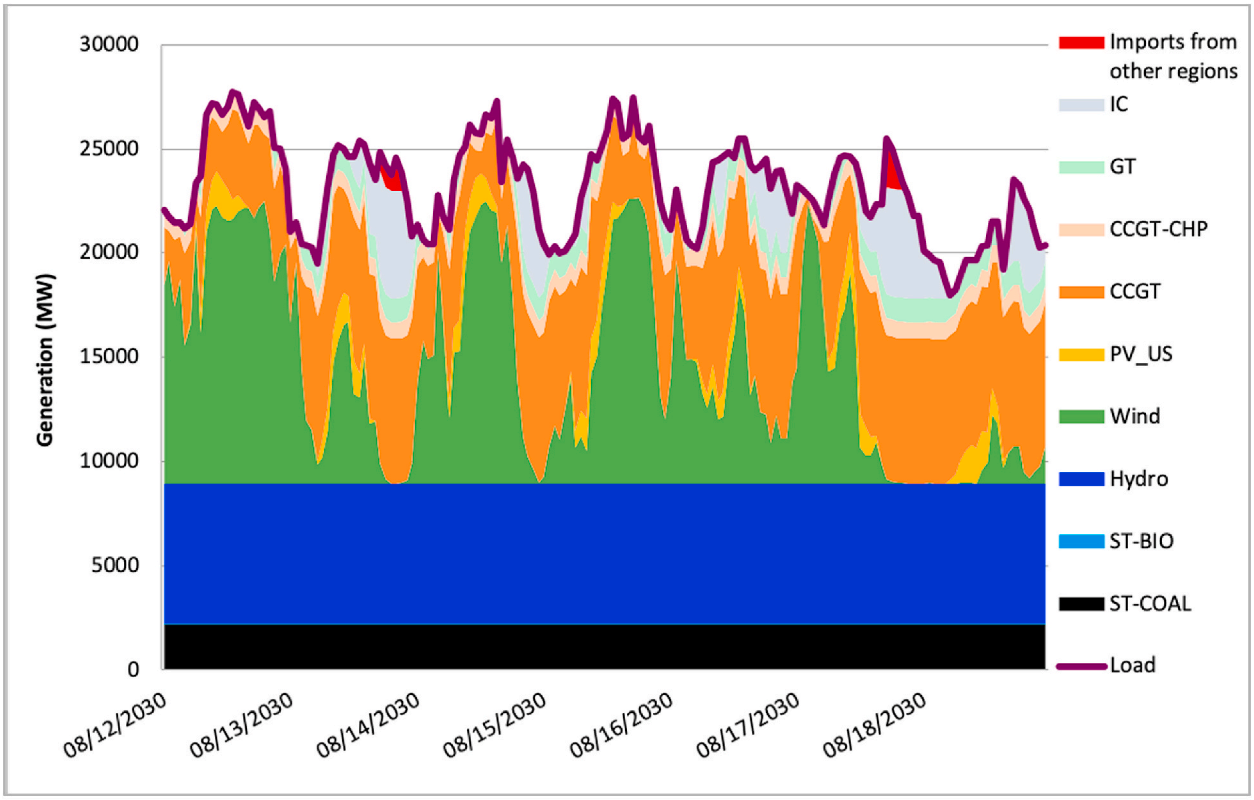
Table 5 presents annualized health outcome results for the three most populated metropolitan areas in NE Brazil, including for a dry year in the 45% VRE case to analyze how lower precipitation levels affect power generation and health impacts. Estimated annual health costs are US$1.38 billion in the 30% VRE scenario, US$0.14 billion in the 45% VRE scenario, US$0.25 billion in the 45% VRE dry year scenario, and zero in the 70% VRE scenario.

The annualized health costs are relatively low compared to other regions with similar electricity demand because NE Brazil's power matrix has higher levels of RE than most countries [43], and its ambient PM concentration is below World Health Organization guidelines [75]. In countries with greater coal and oil power generation, health impacts are much more severe [76,77].

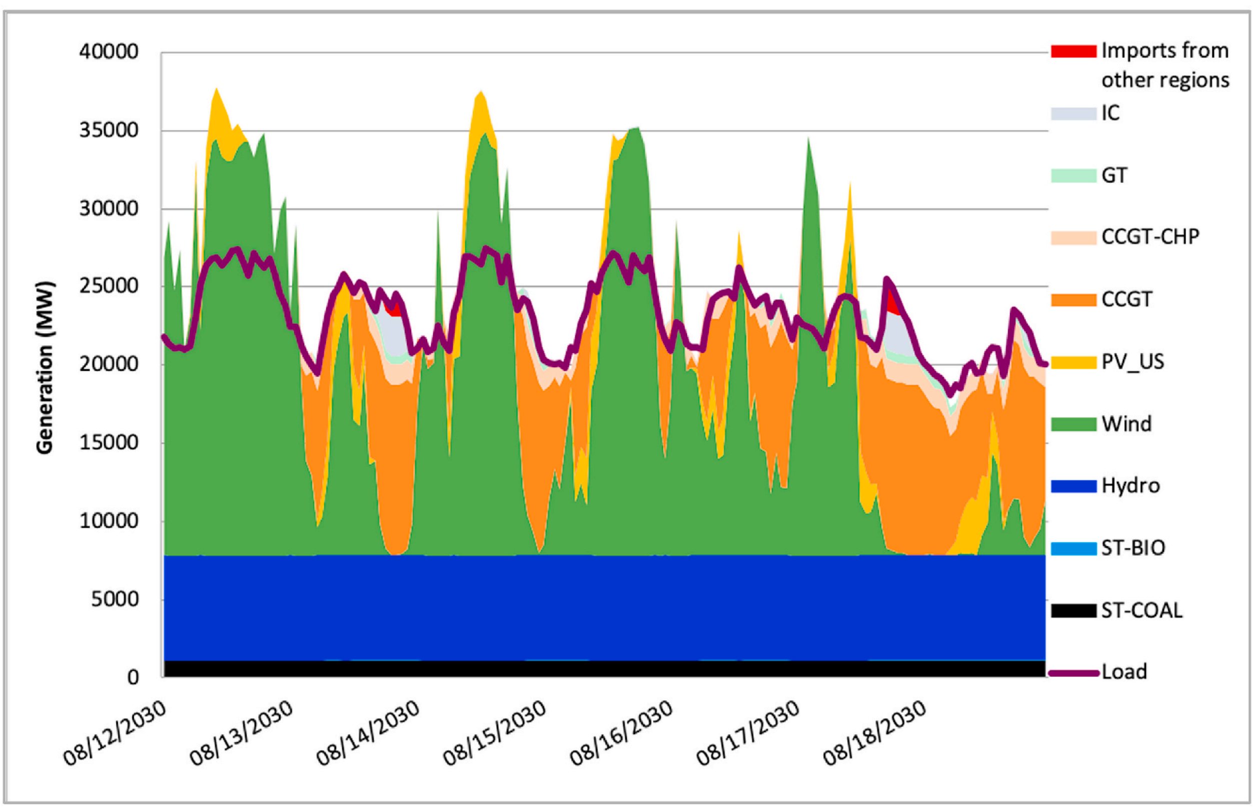
Even under extreme dry year conditions, where water reservoir fill levels and hydroelectric generation constraints are reduced by 30.5%, the health impacts in the 30% VRE scenario are over 5 times greater than in the 45% VRE scenario (see the sensitivity analysis in 5.4 for details.)

5.4. Sensitivity analyses

We analyzed uncertainty in each modeling stage, including power system modeling, infrastructure costs, emission dispersion, and health outcomes. We report here results for four components of our sensitivity analyses in order of decreasing impact on our results: 1) electricity system infrastructure costs; 2) dry year conditions for the 45% VRE; 3) potential impacts of secondary PM; and 4) alternative calculations for

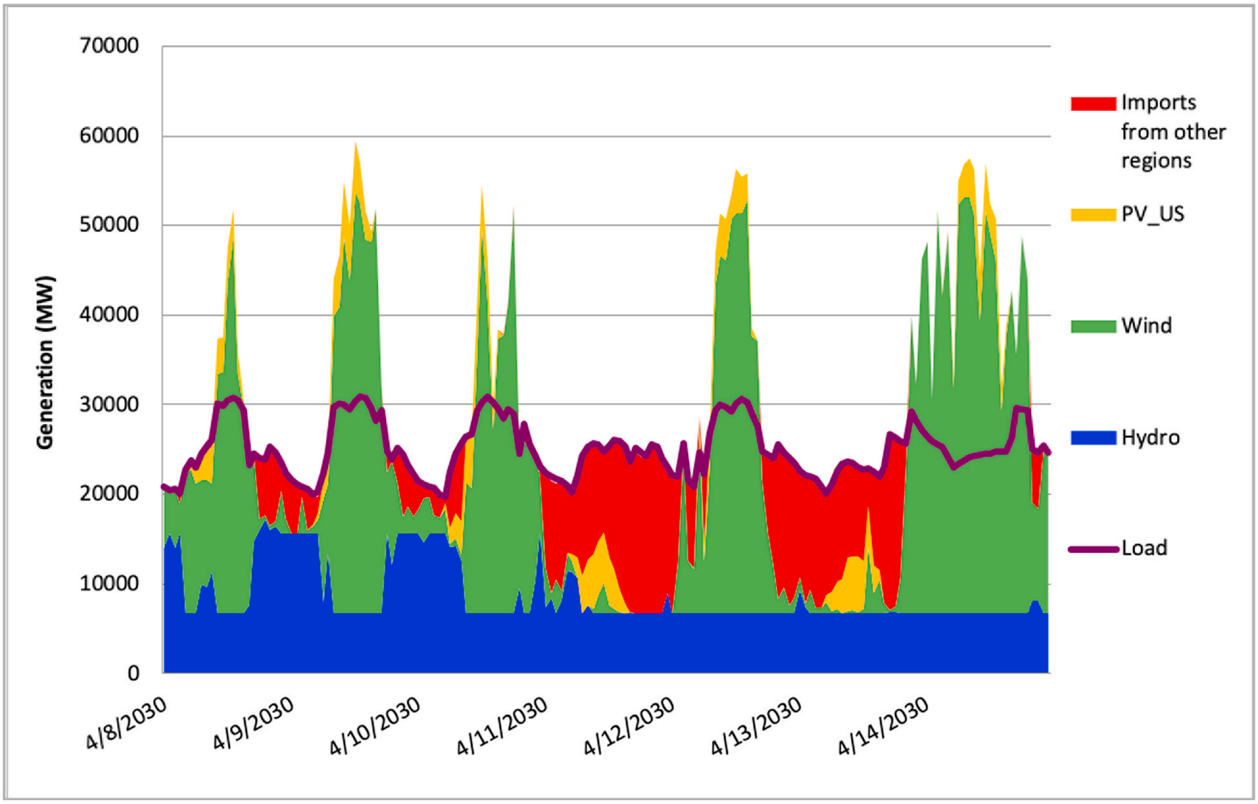


Panel A. 30% VRE



Panel B. 45% VRE

Fig. 4. Electricity dispatch for the week with the highest electricity imports. In Panels A–C above, we used the following abbreviations for electricity generation technologies: PV_US = utility scale photovoltaic; ST-Coal = coal; ST-Bio = bioenergy; GT = conventional gas turbine; CCGT = combined cycle gas turbine; CCGT-CHP = combined cycle gas turbine with combined heat and power; IC = internal combustion engine generator.



Panel C. 70% VRE

Fig. 4. (*continued*).

Table 4
Simulated country-level and global climate costs for NE Brazil in 2030.

	30% VRE	45% VRE	45% VRE dry year	70% VRE
Millions of tonnes of CO_2	48.40	24.20	32.83	0.00
Country-level climate costs (billion $/yr.)	$1.16	$0.58	$0.79	$0.00
Global climate costs (billion $/yr.)	$20.18	$10.09	$13.69	$0.00

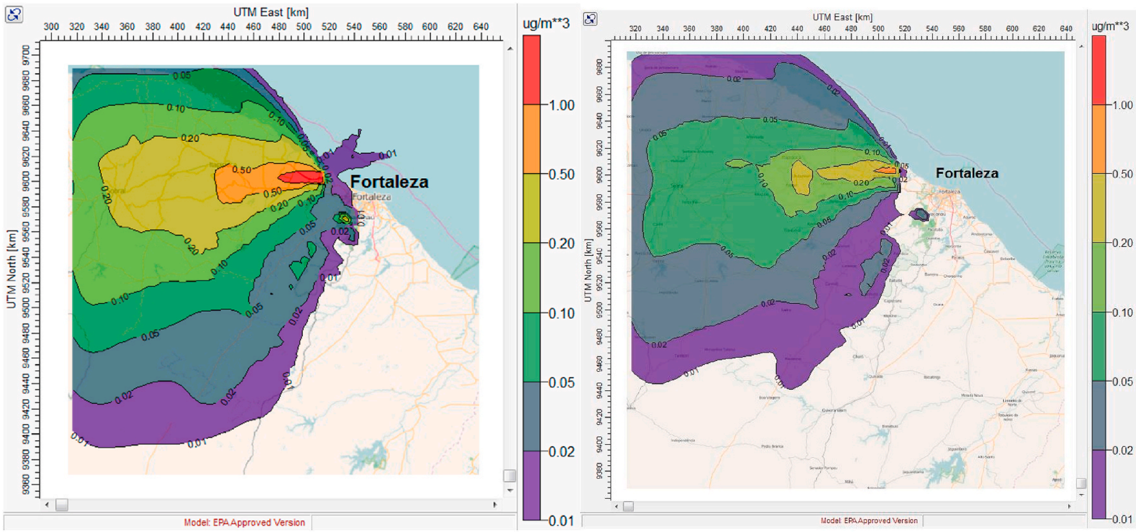
the VSL.

As mentioned above, we relied on the 2010 dataset from Fichter et al. [52] for this study because it is congruent with data from recent studies [53] and with official expansion plans [36]. To analyze uncertainty in electricity system infrastructure costs, we repeated our analyses using data from Barbosa et al. [27], who estimated capital as well as operation and maintenance costs in Brazil's energy sector for 2030. With the 2030 cost data from Barbosa et al. [27], infrastructure costs shrink by 6.1%, 16.1% and 28.9% for the 2030 30% VRE, 45% VRE, and 70% VRE scenarios, respectively. These decreases are driven by substantially lower capital costs for RE technologies in Brazil in 2030, which result from assumptions about global improvements in learning about RE and about growing economies of scale over time for RE. As a result, the sum of infrastructure, climate, and health costs decreases as the level of VRE increases regardless of the price of carbon and the 2030 70% VRE scenario is always preferred, which implies that adding regional health costs to infrastructure costs is sufficient for justifying total decarbonization in the NE Brazil power sector. This result illustrates the importance of infrastructure costs in energy planning, especially when it involves evolving technologies.

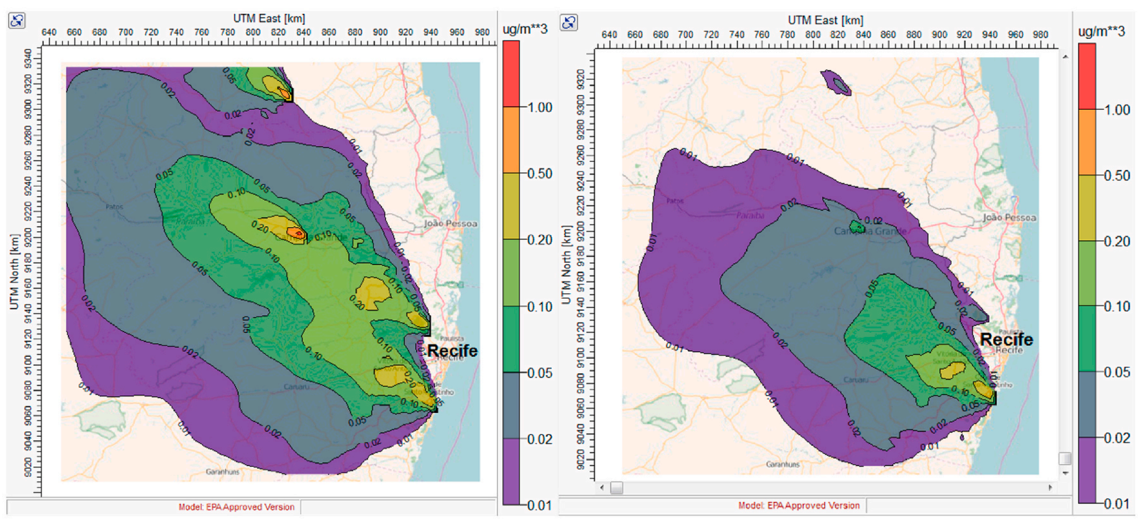
We also analyzed the impact that lower precipitation levels due to climate change could have on the energy-climate-health nexus because Brazil has a large hydroelectric installed capacity (>60% [43]), and recent droughts (e.g., in 2015) have caused the Brazilian government to take measures to decrease the country's dependency on hydroelectricity. To simulate dry year conditions, we reduced water reservoir fill levels and generation constraints by 30.5%, which is the percentage difference between the average annual precipitation and the precipitation for 2012, the driest year in NE Brazil since 1983 [56], and we used 2012 meteorological conditions. Under dry year conditions in the 45% VRE scenario, electricity imports increased from 0.02% to 0.77% of total load, and electricity exports rose from 4.6% to 5.0% of total generation. However, CO_2 emissions soared by 35.6% and $PM_{2.5}$ emissions by 50.9% due to much greater thermal generation, resulting in a 35.6% increase in domestic and global climate costs and in a 77.3% jump in health costs. Precipitation variability is therefore also critically important in Brazil, as well as in other regions dependent on hydroelectricity.

To gauge the extent to which secondary PM formation could increase $PM_{2.5}$ concentrations, we used SCIPUFF (which stands for Second-order Closure Integrated Puff) from Lakes Environmental Inc. and conducted a sensitivity analysis of $PM_{2.5}$ concentrations with ambient air concentrations for O_3, NO_x and VOCs equivalent to those in Southern Texas because these data are not available in our study areas. This is a worst-case scenario because the ambient concentrations of O_3, NOx, VOCs are higher in this surrogate dataset than they are likely to be in our study areas based on the engineering judgement of our Brazilian co-authors. Fig. 6 shows that the average annual secondary $PM_{2.5}$ concentrations for Recife for the 30% VRE scenario are roughly 20% of primary $PM_{2.5}$ concentrations (compare with the right side of Panel B in Fig. 5). This is likely due to the low relative humidity in NE Brazil, which reduces the chemical transformations that result in secondary PM formation.

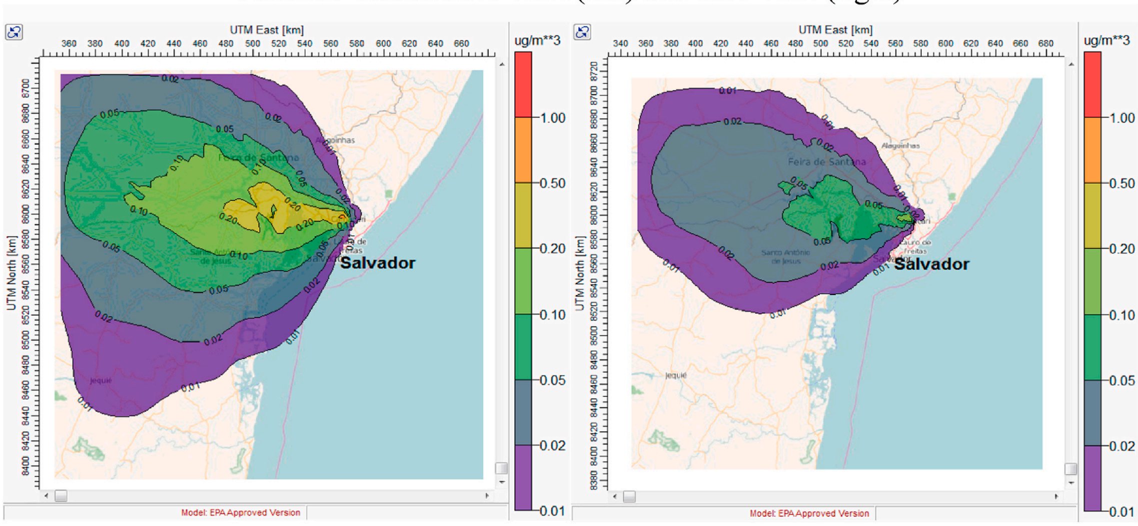
To explore how sensitive our results are to secondary PM, we plotted both the sum of annualized infrastructure plus annual health and carbon costs for the 30% VRE scenario (red dashed line), and the break-even carbon cost above which the 70% VRE scenario is preferred to the



Panel A. Fortaleza 30% VRE (left) and 45% VRE (right)



Panel B. Recife 30% VRE (left) and 45% VRE (right)



Panel C. Salvador 30% VRE (left) and 45% VRE (right)

Fig. 5. Air quality modeling results.

Table 5
Health costs by scenario.

Region/health endpoint	30% VRE (million US $/yr.)	45% VRE (million US $/yr.)	45% VRE dry year (million US$/yr.)
Fortaleza			
Mortality	$71.27	$22.58	$29.43
Infant mortality	$1.29	$0.38	$0.48
Hospital admissions, respiratory	$1.50	$0.44	$0.56
Hospital admissions, cardiovascular	$4.41	$1.30	$1.64
Recife			
Mortality	$1,199.12	$96.70	$178.03
Infant mortality	$7.62	$0.55	$1.02
Hospital admissions, respiratory	$13.83	$1.00	$1.85
Hospital admissions, cardiovascular	$40.70	$2.94	$5.44
Salvador			
Mortality	$40.85	$13.63	$28.73
Infant mortality	$0.23	$0.07	$0.16
Hospital admissions, respiratory	$0.42	$0.14	$0.30
Hospital admissions, cardiovascular	$1.24	$0.41	$0.87
Total Hospital Admissions	$62.09	$6.23	$10.66
Total Mortality	$1,320.38	$133.91	$237.86
Total Health Costs	$1,382.47	$140.14	$248.52

In this table, health costs are shown with two significant digits not to imply precision but because of the wide difference in costs for different outcomes.

45% VRE scenario (blue dotted line), versus the secondary PM health cost multiplier, denoted by μ. μ reflects how much larger health costs could be with secondary PM; μ equals 1 if there is no secondary PM and 2 if there is as much secondary PM as primary PM, doubling health impacts (Fig. 7). The red dashed line shows that annualized infrastructure costs plus annual climate and health cost for the 30% VRE scenario increase only modestly with secondary PM (only 6.8% when μ changes from 1 to 2). The blue dotted line makes a similar case for the break-even carbon cost between the 45% VRE and the 70% VRE cases. For example, when $\mu = 1.6$, the break-even cost of carbon is just 17.5% lower than without secondary PM ($16.36 vs. $19.83). Infrastructure cost uncertainty therefore dominate secondary PM uncertainty here partly because infrastructure costs are substantially larger than health costs.

Finally, since premature mortality drives our health outcome results, we derived an alternative value for the VSL by linearly extrapolating the US VSL for 2026 (the most recent projection available) to 2030 and then converting it to a 2030 VSL for Brazil using Eq. (2). The resulting VSL of US$7,202,908 differs by only 4.4% from the VSL calculated using the method recommended by the US EPA, which is small here compared to the other sources of uncertainty.

5.5. Limitations

One limitation of our work is that we modeled only one of the five electric grids in Brazil in order to keep this project manageable. Modeling the interaction of all grids at the transmission level along with distribution level power system flow and frequency control would be necessary for analyzing the technical feasibility of moving to higher levels of VRE and for fully estimating infrastructure costs. A second limitation is that the natural and anthropogenic emissions inventories required for modeling secondary PM are not available in Brazil (Sogabe, M.N., Environmental Company of the State of Sao Paulo, personal communication, 2018). Third, more information about the spatial distribution of the population in our study areas and Brazil-specific C-R functions for a wider range of age groups and of health outcomes would have allowed more extensive analyses, although our results cover the

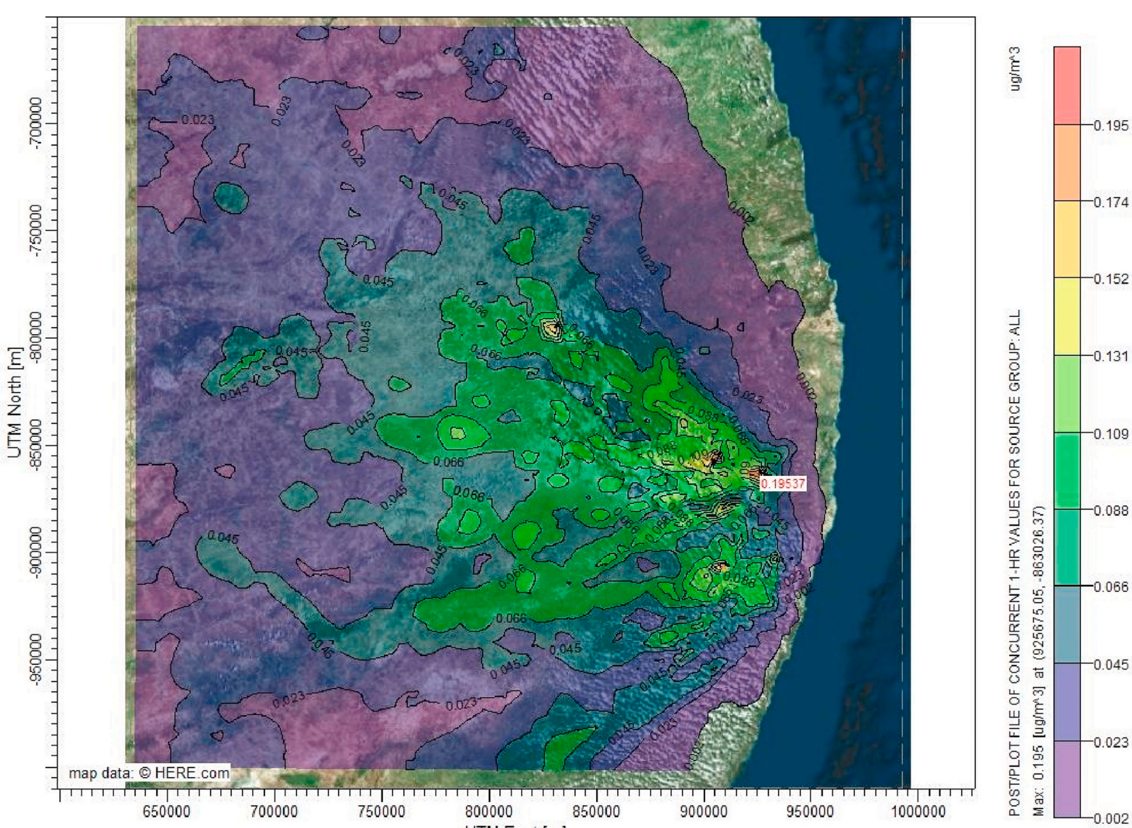


Fig. 6. Average annual secondary $PM_{2.5}$ concentrations for Recife in the 30% VRE scenario.

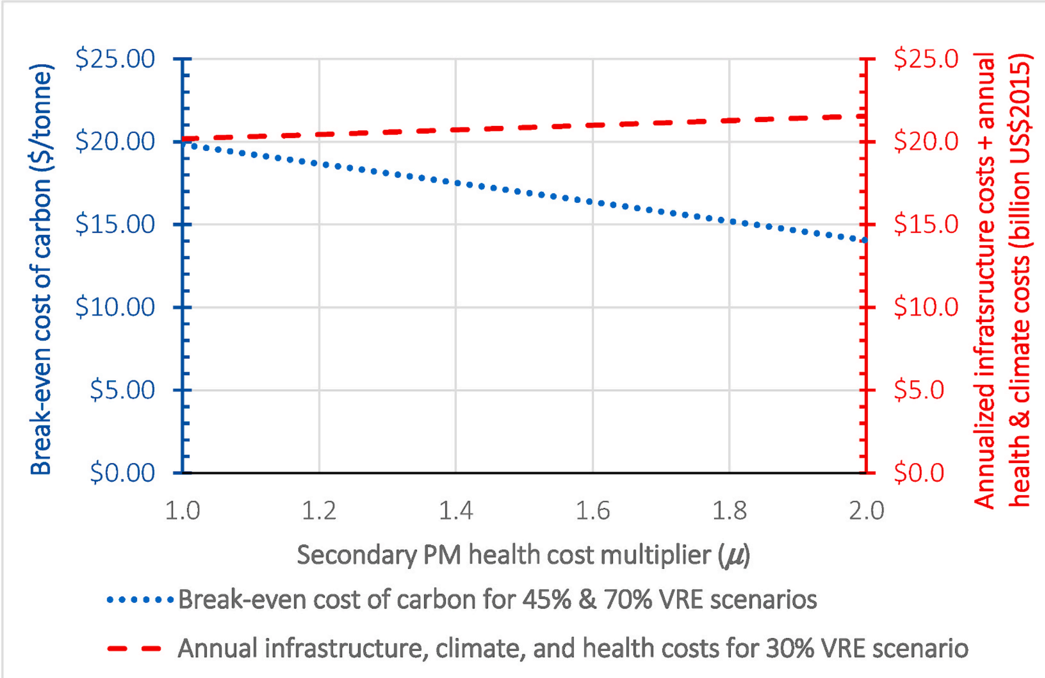


Fig. 7. Sensitivity analysis for secondary $PM_{2.5}$ concentrations.

most severe health impacts. Finally, the GSCC only includes countries where data are available [60].

As a result of data limitations, our infrastructure, climate, and health costs are conservative for several reasons. First, our infrastructure costs do not include the cost of additional transmission system infrastructure, although we did ensure that the forecasted 2030 transmission system capacity between regions was not exceeded. Second, as mentioned above, our health costs do not include the impact of secondary PM. Third, we were unable to consider mortality caused by PM exposure outside of the five main causes in the IER or in people between the ages of 1 and 25. Fourth, our three air quality modeling areas (see Fig. 2) cover only the main metropolitan areas of NE Brazil, although our electricity grid emissions simulations indicate that PM emissions from energy generation outside these areas are small. Additionally, the domestic and global climate cost estimates due to NE Brazil's power system do not account for some of the long-term impacts of climate change.

6. Conclusions and future work

When the price of carbon exceeds $20/tonne, which is $4 below Brazil's country-level social cost of carbon (CSCC), it is economically preferable to switch from the 45% VRE to the 70% VRE scenario and fully decarbonize the electricity production sector. This suggests that taking into account the country-level climate costs and health impacts in our study area is sufficient to economically justify moving to a carbon-neutral energy system. Even when climate impacts are ignored and carbon is unpriced, the sum of infrastructure and health costs in the 45% VRE scenario is less than the 30% VRE scenario, so accounting for health impacts alone is sufficient to economically justify deep decarbonization in our study area.

If the regional climate and health impacts outweigh the additional infrastructure costs of decarbonization in NE Brazil, we surmise that this also holds for a number of other regions around the world. Indeed, while Brazil's CSCC is relatively high compared to other countries [60], the health and climate costs due to the power sector are relatively low because RE makes up ~80% of Brazil's electricity infrastructure capacity [43] and contributed ~60% of the electricity generated in 2015 [78].

In future energy-climate-health nexus studies, we recommend modeling the interconnection of electricity grids along with new types of dispatchable RE sources, load balancing and energy storage options. These include CSP with thermal energy storage, hybrid solar-biomass, waste-to-energy, renewable synthetic natural gas and biogas, batteries, power-to-gas, adiabatic compressed air energy storage and sector coupling. It would also be valuable to optimize the relative proportion of wind and solar VRE. In addition, modeling distribution scale dynamics and estimating transmission and distribution system costs along with secondary PM impacts and a sensitivity analysis of climate impact costs would provide additional valuable insights.

We also recommend modeling the energy-climate-health nexus in areas with a wide range of power mixes, population distributions, renewable energy resources, and electricity grid dynamics. Furthermore, it would be of interest to investigate alternative modeling strategies to estimate the optimal level of regional/countrywide RE and VRE while accounting for climate and health costs, and to estimate the marginal health and climate costs of electricity generation units so they can be included in optimizing electricity dispatch. While in this study we relied on scenario analysis because assessing health impacts was very time and data intensive, we recommend exploring the feasibility of using power system capacity expansion optimization modeling to analyze the energy-climate-health nexus. As illustrated by our results, including health impacts in energy planning is essential because they can be sufficient to economically justify deep decarbonization.

In order to meet the Paris Agreement and the Sustainable Development Goals, nearly all countries need to urgently and drastically increase their climate action [3]. Accounting for health and climate costs in energy planning would provide an economic justification for decarbonizing energy systems, as well as reduce the social cost of supplying electricity, boost the economy and improve the quality of life. Although we focused here on Northeast Brazil, our methodology is applicable to developed and developing countries alike. This paper is therefore a call to systematically account for health and climate costs in energy planning worldwide.

Credit author statement

Conceptualization: Daniel Howard and Jean-Daniel Saphores, Data preparation: Daniel Howard, with assistance from Jesse Thé, Rafael Soria, and Roberto Schaeffer, Methodology and formal analysis: Daniel Howard, with advice from Jean-Daniel Saphores, Jesse Thé, Rafael Soria, and Roberto Schaeffer, Writing: Daniel Howard and Jean-Daniel Saphores, with editing from Jesse Thé, Rafael Soria, and Roberto Schaeffer.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110016.

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