Health Impact Assessment
CREA HIA

Air quality impacts of the Ternium Brasil Santa Cruz steel plant

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CREA
Centre for Research on Energy and Clean Air

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The Centre for Research on Energy and Clean Air (CREA) is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution. CREA uses scientific data, research, and evidence to support the efforts of governments, companies, and campaigning organisations worldwide in their efforts to move towards clean energy and clean air, believing that effective research and communication are the keys to successful policies, investment decisions, and advocacy efforts. CREA was founded in Helsinki and has staff in several Asian and European countries.

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Air quality impacts of the Ternium Brasil Santa Cruz steel plant

Key findings

- This report assesses how emissions from the steel facility located in Santa Cruz, Rio de Janeiro, currently known as Ternium Brasil Santa Cruz (formerly CSA Cia Siderúrgica do Atlántico), have affected air quality, public health, and the economy during its operations from 2010 to 2023.
- The Ternium Brasil steel facility emits dangerous levels of toxic air pollutants over a wide region, extending as far as São Paulo.
- Exposure to the pollutants emitted by Ternium Brasil has led to a devastating impact on the health of the local population.
- Some of the estimated health impacts caused by exposure to pollution from Ternium Brasil include 100 (70–150) visits to the emergency room due to asthma, 300 (60–700) new cases of asthma in children, 1,100 (300–2,400) children suffering from asthma, 60 (20–110) preterm births, 60 (20–110) low birth weights, and 120,000 (100,000–140,000) days of work absences.
- In addition, air pollution from this facility is estimated to have led to 1,200 (775–1,750) deaths due to diseases including stroke, lower respiratory infections, chronic obstructive pulmonary disease, lung cancer, and diabetes - this includes the death of approximately 35 (10–65) children under the age of 5 years old.
- Considering these health outcomes, air pollution from Ternium Brasil could have cost society USD 1.8 (1.2–2.7) billion, or BRL 9.1 (5.8–13.2) billion.
- For context, the economic costs due to air pollution from Ternium Brasil exceed Rio de Janeiro's combined expenses in education, culture, and sports for an entire year (BRL 8 billion) (Statista, 2023).
- Overall, the Ternium Brasil steel facility, which is powered by dirty fuels, including coal and coke, and lacks air pollution control measures, has had a devastating impact on public health and the economy, including millions of dollars in health damages.

Contents

Introduction

Air pollution has a detrimental impact on the global environment, public health, and economy. Exposure to air pollutants, such as particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2), leads to negative impacts on nearly all the major systems and organs of the human body, including the respiratory, cardiovascular, and reproductive systems, as well as the brain, heart, and lungs. Health outcomes range from asthma in adults and children, to preterm and underweight births in pregnant women, and work absences due to respiratory illnesses. In some cases, exposure to air pollution can even lead to death, through diseases including ischaemic heart disease, chronic obstructive pulmonary disease, lung cancer, lower respiratory infections, and diabetes (Lelieveld et al., 2019; Di et al., 2017; WHO, 2021).

Globally each year, the impacts of exposure to air pollution include 2 million paediatric asthma cases (Anenberg et al., 2022), 1 billion days of work absences, (OECD, 2016), and over 6 million deaths (Lelieveld et al., 2019). As a result of these health consequences, air pollution costs the global economy USD 8 trillion (World Bank, 2022).

In Brazil, exposure to $PM_{2.5}$ leads to 58,000 deaths and USD 52 billion in health damages each year (World Bank, 2022). In many regions of the country, pollutant levels exceed the guideline values set by the World Health Organization (WHO)(IQAir, 2021; Li & Zhu, 2014).

The steel industry emits both greenhouse gases, which are contributing to climate change, as well as toxic air pollutants which are damaging to human health (Dai et al., 2015). Toxic air pollutants that are emitted during steel production include sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), and heavy metals. Pollutants are emitted throughout the steel production process, including during coking, sintering, iron making, steel making, and finishing (Conejo et al., 2020; He & Wang, 2017). The steel industry accounts for more than 5 % of the world's energy demand and is the leading consumer of energy in the industrial sector (Conejo et al., 2020; Li & Zhu, 2014). As a consequence, steel production accounts for about 11% of global CO_2 emissions (Carbon Brief, 2021).

Field studies have revealed high levels of air pollution around steel facilities across North America, South Korea, and Nigeria (Kousehlar & Widom, 2020; Owoade et al., 2015). CREA's previous research has found that emissions from the European iron and steel industry lead to 2,570 deaths each year, which has an economic burden of EUR 7 billion (Myllyvirta et al., 2023). $PM_{2.5}$ metal components are associated with acute changes in cardiovascular and respiratory physiology, inducing increases in blood pressure and loss of lung function up to 4% of total lung capacity (Cakmak et al., 2014). In addition, the benzol refinement section of the steel industry, which is an important source of benzene emissions, can lead to cancer (Dehghani et al., 2018). The health impacts of air pollution from steel have a huge cost to society, through reductions in the supply of labour and increases in the costs of medical treatment (Yao et al., 2020).

Brazil plays a crucial role in the global steel sector. The demand for steel in Brazil has risen by 4.5% per year from 1970 to 2013 (Torres de Souza & Pacca, 2021). Moreover, 40% of the steel produced in the country is exported, making Brazil the 6th largest net exporter (Torres de Souza & Pacca, 2021). As a result, the steel industry in Brazil plays an important role in Brazil's economy. The steel industry has become successful due to the high availability of high-quality iron ore, the low cost of labour, and the position of the country in a logistically favourable location (IndustriAll, 2022). There are 31 steel plants across the country, located across 10 different states (Trovão et al., 2022). These steel plants run mostly on low-quality imported coal, and when burnt, they emit large quantities of CO_2 (IEA, 2023). Currently, this sector is responsible for around 25% of the country’s industrial GHG emissions (Hebeda et al., 2023). In 2023, 38-52 million tons of CO_2 was emitted from Brazil’s steel sector (GEM, 2024). The dangerous climate impacts of Brazil’s steel sector could be reduced by using steelmaking gas to produce electricity, installing dry coke quenching technology, and replacing the manganese ore supply in steelmaking (Trovão et al., 2022).

Ternium steel manufacturing company was founded in 2005 and is a leading steel producer in the Americas, producing around 12.5 million tonnes of crude steel and creating USD 16 billion in profit annually (Ternium, 2023b; Macrotrends, 2024). It has 18 production facilities located across Argentina, Brazil, Colombia, Guatemala, Mexico, and the United States. Ternium collaborates with Brazil’s largest steel company, Usiminas, in its quality control. The company has facilities working at all stages of steel production from mining iron ore to the creation of final products (Ternium, 2023a). Ternium has been ranked in the 90th percentile in the basic iron and steel manufacturing industry based on its policies, procedures, and actions related to environmental and labour practices, sustainable procurement, and ethics (Ternium, 2023b).

The steel facility located in Santa Cruz, Rio de Janeiro, was commissioned in 2010 by the CSA Cia Siderúrgica corporation, which was a joint venture between Vale and

Thyssenkrupp. In 2016, Vale sold its stake in CSA Cia Siderúrgica to Thyssenkrupp, making the latter the sole owner of CSA Cia Siderúrgica. In 2017, CSA Cia Siderúrgica was sold to Ternium. The steel plant has a capacity of 5,200 thousand tonnes per annum (TTPA) — or 5 million tonnes — of steel per year. The plant utilises a blast furnace and a basic oxygen furnace in its steel production. End users of the facility's steel include the automotive, building and infrastructure, energy, tools and machinery, and transport sectors (GEM, 2023).

In this health impact assessment (HIA) report, we estimated how emissions from the Ternium Brasil steel plant located in Santa Cruz, Rio de Janeiro (Brazil) have contributed to air pollution (NO_2, SO_2, $PM_{2.5}$), and how exposure to these pollutants has affected public health and the economy over the period that the plant has been running (2010–2023). To achieve this, we used pollutant emissions reported by Ternium Brasil in an industry-standard air pollution model (Exponent, 2015) that allows us to calculate pollutant levels in the atmosphere, followed by combining pollutant exposure levels with peer-reviewed data on the relationship between air pollution and health outcomes (Myllyvirta, 2020). This general methodology, as well as the specific tools, are all widely used by scientists and governments worldwide (Schucht et al., 2021; EPA, 2011; Zhang et al., 2019), and are based on data that has been established through decades of scientific research. See the Methodology section for a detailed description of the methodology.

Results

Environmental levels of pollution

For this study, we simulated how the Ternium Brasil steel plant contributes to the formation of the atmospheric pollutants $PM_{2.5}$, NO_2, and SO_2. Figure 1 shows the impact of emissions from Ternium Brasil on local annual average $PM_{2.5}$. In the immediate vicinity of Ternium, concentrations of annual mean $PM_{2.5}$ reach 0.60 µg/m^3.

However, as $PM_{2.5}$ can remain in the atmosphere for up to two weeks, it does not only affect local communities. Moderate levels of $PM_{2.5}$ (0.1 μg/m^3) envelop the western metropolitan area of Rio de Janeiro, while the main plume of pollution is transported towards the south-west of the facility, almost reaching São Paulo. Emissions from Ternium Brasil lead to the formation of multiple pollutants in the atmosphere that have long-range impacts on the Brazilian population.

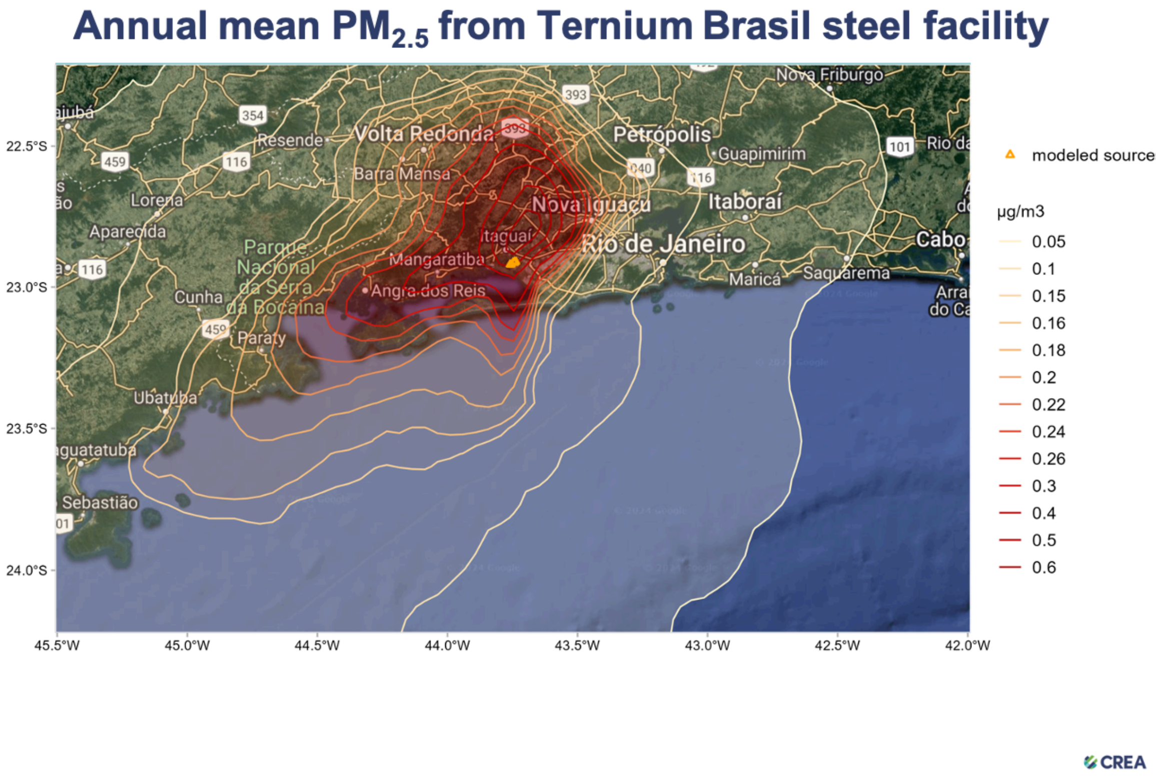

Annual mean $PM_{2.5}$ from Ternium Brasil steel facility

Figure 1 – Annual mean $PM_{2.5}$ concentration from the Ternium Brasil steel facility

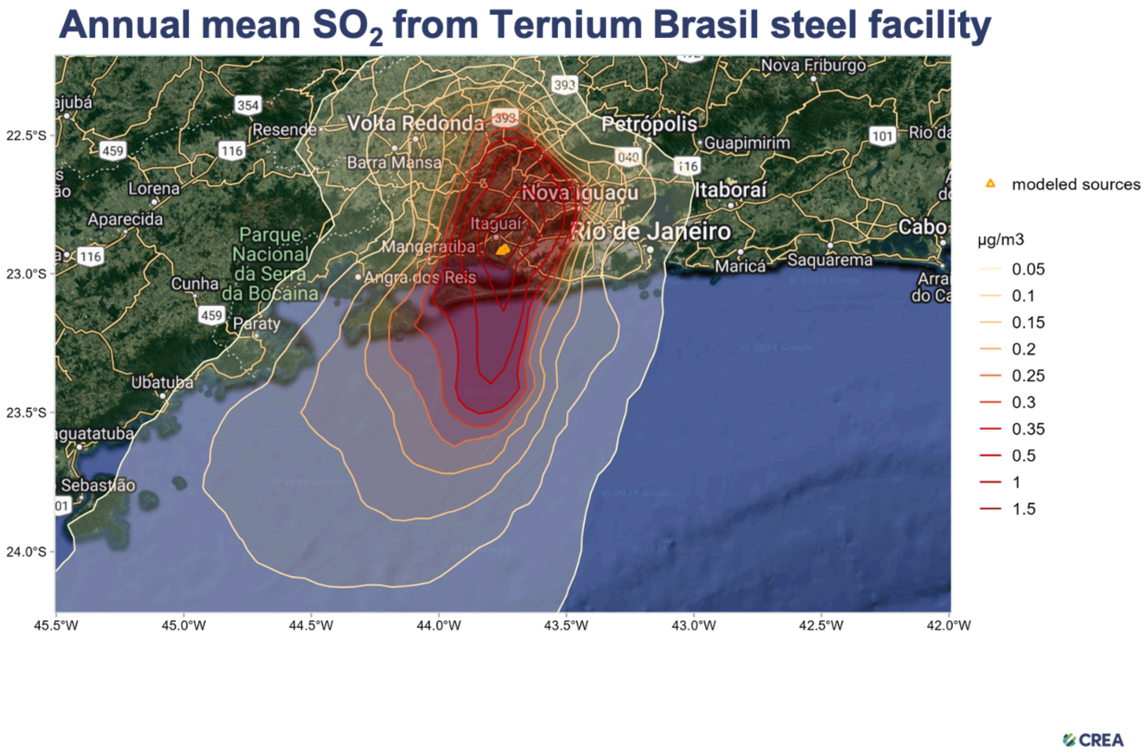

Annual mean SO_2 from Ternium Brasil steel facility

Figure 2 – Annual mean SO_2 concentration from the Ternium Brasil steel plant

Health impacts of pollution

For this study, we calculated how human exposure to air pollutants ($PM_{2.5}$, NO_2, and SO_2) from the steel facility in Santa Cruz, Rio de Janeiro, currently known as Ternium Brasil Santa Cruz (formerly CSA Cia Siderúrgica do Atlántico), affects public health and the economy. Table 1 shows the estimated deaths caused by pollution from the facility, integrated over the whole period that it has been operating (2010–2023). Exposure to all pollutants ($PM_{2.5}$, NO_2, SO_2) is estimated to have led to 1,200 (775–1,750) deaths, with the range reflecting the upper and lower confidence intervals of the pollutant dose-response functions (Table 5). For $PM_{2.5}$, we have a breakdown of how people have died, with estimates indicating that this pollutant has led to over 330 deaths among the adult population due to ischaemic heart disease (160), stroke (70), lower respiratory infections

(35), chronic obstructive pulmonary disease (30), lung cancer (15), and diabetes (10), as well as lower respiratory infections in children under the age of 5 (35).

Table 1 – Deaths due to exposure to air pollution from the Ternium Brasil steel facility (2010–2023)

Cause of death	Pollutant	Age group	Death rates
All-cause mortality	$PM_{2.5}$, NO_2, SO_2	Adults and children	1,200 (775–1,750)
All-cause mortality	$PM_{2.5}$	Adults and children	330 (240–445)
All-cause mortality	NO_2	Adults and children	720 (440–1,090)
All-cause mortality	SO_2	Adults and children	150 (90–215)
Ischaemic heart disease	$PM_{2.5}$	Adults	160 (120–200)
Stroke	$PM_{2.5}$	Adults	70 (25–120)
Lower respiratory infections	$PM_{2.5}$	Adults	35 (10–65)
Chronic obstructive pulmonary disease	$PM_{2.5}$	Adults	30 (10–55)
Lung cancer	$PM_{2.5}$	Adults	15 (10–30)
Diabetes	$PM_{2.5}$	Adults	10 (2–17)
Lower respiratory infections	$PM_{2.5}$	Children	35 (10–65)

Table 2 shows the impacts of air pollution from the Ternium Brasil Santa Cruz steel facility (operating as CSA Cia Siderúrgica do Atlántico from 2010 to 2017) on human morbidity outcomes from 2010 to 2023. Air pollution severely damages the respiratory system, and in particular, the lungs. As a result, air pollution from Ternium Brasil is estimated to have led to 100 (70–150) visits to the emergency room due to asthma. Children are particularly sensitive to these health impacts, as their lungs are underdeveloped. Consequently, air pollution from the Santa Cruz facility is estimated as having resulted in 300 (60–700) new cases of asthma in children, and approximately 1,100 (300–2,400) children suffering from asthma overall. Pregnant women are particularly susceptible to the negative impacts of pollution due to the impacts of air pollution on the reproductive system and foetuses. Because of this, air pollution from Ternium Brasil is estimated as having led to 60 (20–110) preterm births and 60 (20–110) low birth weights. As a result of the large impact on public health, air pollution from Ternium is estimated as having led to 120,000 (100,000–140,000) days of work absences.

Table 2 – Morbidity impacts due to exposure to air pollution from the Ternium Brasil steel facility (2010–2023)

Health outcome	Rate
Asthma ER visits	100 (70–150)
New cases of asthma in children	300 (60–700)
Number of children suffering from asthma	1,100 (300–2,400)
Low birthweight births	60 (20–110)
Preterm births	90 (45–100)
Work absences (sick leave days)	120,000 (100,000–140,000)

Economic impacts of pollution

The health impacts due to air pollution from the Ternium Brasil Santa Cruz steel facility (formerly CSA Cia Siderúrgica do Atlántico) have a significant impact on the economy. Air pollution from the 2010 to 2023 operations of the Santa Cruz facility is estimated to have cost society USD 1.8 (1.2–2.7) billion, which is equivalent to BRL 9.1 (5.8–13.2) trillion. For comparison, this cost exceeds Rio de Janeiro's combined expenses in education, culture, and sports for an entire year (BRL 8 billion) (Statista, 2023).

Table 3 – The economic cost of health damages due to exposure to air pollution from the Ternium Brasil steel facility

Currency	2010-2023
USD	1.8 (1.2–2.7) billion
BRL	9.1 (5.8–13.2) billion

Methodology

In this study, we estimated how pollutant emissions from the Ternium Brasil steel plant have affected air quality, public health, and the economy, whilst this facility has been in operation (2010–2023). Firstly, we retrieved pollutant emissions data from Ternium official documents. Secondly, we used a meteorological and air dispersion model to simulate how emissions from the facility are transported in the atmosphere, generating maps of the distribution of pollutants in the atmosphere. Thirdly, we calculated how exposure to the pollutants affects public health by combining the maps of pollutant concentrations with data that describes the toxicity of the pollutants and population data (e.g. population density, age, baseline health incidence, etc.).

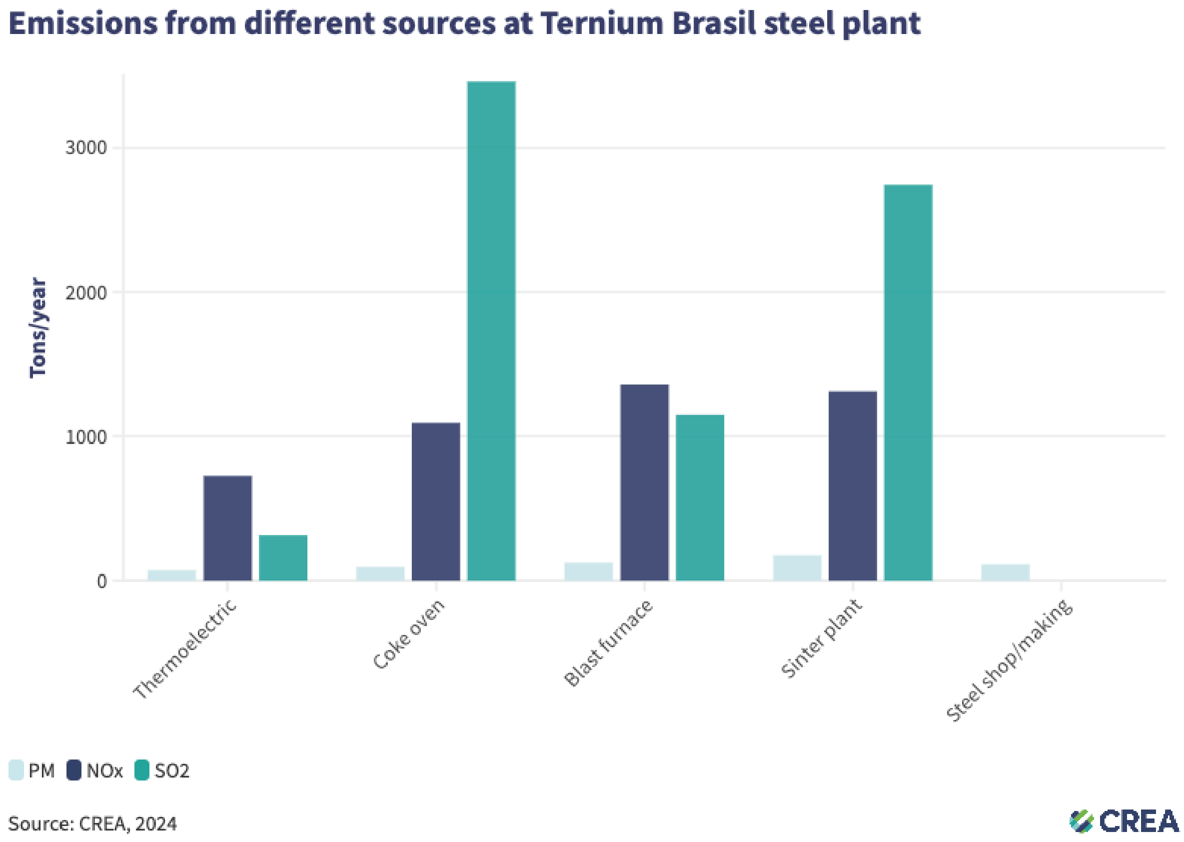
Pollutant emissions

From official Ternium Brasil documents (Government of the State of Rio de Janeiro, 2021), we retrieved data on pollutant emissions and stack characteristics. Results from this data retrieval are shown in Table 4, Table 5, and Figure 3.

Table 4 – Stack information

Stack	Type	Location		Height	Diameter	Flue gas volume	Flue gas temperature
		Latitude	Longitude				
GT 11	Thermoelectric	22°54'40.69"S	43°44'41.66"W	40	5.50	641240.7273	150
GT 12	Thermoelectric	22°54'40.69"S	43°44'41.66"W	40	5.6	512992.5818	150

Coqueria FGD A	Coke oven	22°55'9.94" S	43°45'25.59"W	60	4.5	388048	150
Coqueria FGD B	Coke oven	22°55'9.94" S	43°45'25.59"W	60	4.5	388048	150
Coqueria FGD C	Coke oven	22°55'9.94" S	43°45'25.59"W	60	4.5	388048	150
Britador de carvão (C17)	Coke oven	22°55'9.94" S	43°45'25.59"W	15	1.2	21600	30
Carregamento de Carvão (C85) A	Coke oven	22°55'9.94" S	43°45'25.59"W	20	1.5	52000	30
Carregamento de Carvão (C85) B	Coke oven	22°55'9.94" S	43°45'25.59"W	20	1.5	52000	30
Carregamento de Carvão (C85) C	Coke oven	22°55'9.94" S	43°45'25.59"W	20	1.5	52000	30
Casa de estocagem	Blast furnace	22°54'36.09"S	43°44'23.29"W	35	3.6	512640	30
Casa de corrida	Blast furnace	22°54'36.09"S	43°44'23.29"W	35	5.39	1440000	30
Poço de emergência	Blast furnace	22°54'36.09"S	43°44'23.29"W	40	3.2	360000	30
Altos fornos 1/regenerador 1	Blast furnace	22°54'36.09"S	43°44'23.29"W	60	4.5	388048	150
Altos fornos 2/regenerador 2	Blast furnace	22°54'36.09"S	43°44'23.29"W	60	4.5	388048	150
PCI 1	Blast furnace	22°54'36.09"S	43°44'23.29"W	63	1.5	60000	30
PCI 2	Blast furnace	22°54'36.09"S	43°44'23.29"W	63	1.5	60000	30
Primary dedusting (PE1)	Sinter plant	22°54'47.96"S	43°44'36.90"W	85	5.5	979200	150
Secondary dedusting (PE2)	Sinter plant	22°54'47.96"S	43°44'36.90"W	60	3.3	360000	30
Secundário da aciaria	Steel shop/ making	22°54'31.79"S	43°44'19.65"W	30	6.8	1225600	30


Emissions from different sources at Ternium Brasil steel plant

Source: CREA, 2024

Figure 3 – Emissions from different sources at Ternium Brasil steel facility

Table 5 – Annual total pollutant emissions from Ternium Brasil steel facility

Pollutant	Annual emission (tonnes/year)
$PM_{2.5}$	520
NO_X	4,490
SO_2	7,670

Atmospheric modelling

For this study, we simulated air pollutant concentrations using the CALPUFF air dispersion model, version 7 (Scire et al., 2000; Exponent, 2015). CALPUFF has been a widely-used industry standard model for long-range air quality impacts of point sources, and used by both regulators, such as the US Environmental Protection Agency (US EPA) (US EPA, 2023) and in academic research (Zhang et al., 2020). Due to its capability of capturing the complex chemical processes and atmospheric transport of pollutants in the atmosphere, the US EPA officially approves the use of the CALPUFF model to investigate the cases where an emission source is expected to lead to the long-range transport of pollution (US EPA, 2023). The model has been evaluated extensively by the US Environmental Protection Agency, is open-source, and fully documented. The CALPUFF model has been applied in many regions around the world, including the United States (Rzeszutek, 2019), Europe (Holnicki et al., 2016), Central America (Hernández-Garcés et al., 2020), South America (Arregocés et al., 2023), the Middle East (Ghannam & El-Fadel, 2013), Asia (Zhou et al., 2003; Jittra et al., 2015), and Africa (Affum et al., 2016).

CALPUFF calculates the atmospheric transport, dispersion, chemical transformation, and deposition of the pollutants, and the resulting incremental ground-level concentrations attributed to the studied emissions sources. Chemical transformations of SO_2 and NO_2 to $PM_{2.5}$ are calculated using ISORROPIA. Background concentrations of oxidants (ozone, ammonia, hydrogen peroxide) are taken from a global atmospheric chemistry model. Meteorological input data for the year 2021 are generated from the Weather Research Forecasting (WRF) model (Skamarock et al., 2008), version 4.2.2. WRF was set up with 33 vertical levels and 2 nested grids. The mother nest has a grid resolution of 15 km and spans 1,500 km in both the north-south and east-west directions. The inner nest has a grid resolution of 3 km, spans 300 km in both the north-south and east-west directions, and is centred over the Ternium Brasil steel plant.

Mother and inner domains use a two-way nesting technique which ensures dynamic interaction between them. WRF simulations use initial and lateral boundary conditions from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFRS) dataset of the National Oceanic and Atmospheric Administration (NOAA) producing three-dimensional, hourly meteorological data covering the full calendar year of 2021.

For assessment of annual average pollutant concentrations, emissions are assumed constant throughout the year. Emissions from each of the ten units were modelled as separate area sources. The power plants were modelled as buoyant point sources, taking into account the stack height and thermal plume rise from the stacks.

Health and economic impact assessment

Based on the spatial distributions of pollutants simulated by the CALPUFF air dispersion model, we then calculated the corresponding public and economic impacts for the year 2022. CREA has developed a detailed globally implementable health impact assessment (HIA) framework based on the latest science (Myllyvirta, 2020). This framework includes as complete a set of health outcomes as possible without obvious overlaps.

The emphasis is on outcomes for which incidence data is available at the national level from global datasets and outcomes that have high relevance for healthcare costs and labour productivity. These health endpoints were selected and quantified in a way that enables economic valuation, adjusted by levels of economic output and income in different jurisdictions.

For each evaluated health outcome, we have selected a concentration-response relationship that has been used to quantify the health burden of air pollution at the global level in peer-reviewed literature. This indicates that the evidence is mature enough to be applied across varying geographies and exposure levels. The calculation of health impacts follows a standard epidemiological calculation:

$$\Delta cases = Pop \times \sum_{age} \left[Frac_{age} \times Incidence_{age} \times \frac{RR_{c,age} - 1}{RR_{c,age}} \right],$$

Where:

Pop is the total population in the grid location;

age is the analysed age group; in the case of age-dependent concentration-response functions, a 5-year age segment; in other cases, the total age range to which the function is applicable;

$Frac_{age}$ is the fraction of the population belonging to the analysed age group;

$Incidence$ is the baseline incidence of the analysed health condition;

c is the pollutant concentration with c_{base} referring to the baseline concentration or current ambient concentration; and,

$RR_{conc,\ age}$ is the function giving the risk ratio of the analysed health outcome at the given concentration for the given age group compared with clean air. In the case of a log-linear, non-age specific concentration-response function the RR function becomes:

$$RR(c) = RR_0 c - c_0 \Delta c_0 \ when\ c > c_0, \text{1 otherwise}$$

Where:

RR_0 is the risk ratio found in epidemiological research;

Δc_0 is the concentration change that RR_0 refers to; and,

c_0 is the assumed no-harm concentration — in general, the lowest concentration found in study data.

Data on the total population and population age structure was taken from the Global Burden of Disease results for 2019 (Murray et al., 2020), which was accessed by the Institute for Health Metrics and Evaluation (IHME, 2020). The spatial distribution of the population within each city and country, as projected for 2020, was based on the Gridded Population of the World v4 from the Center for International Earth Science Information Network (CIESIN, 2018).

Adult deaths were estimated using the risk functions developed by Burnett et al. (2018), as applied by Lelieveld et al. (2019). Deaths of small children under five years old from lower respiratory infections linked to $PM_{2.5}$ pollution were assessed using the Global Burden of Disease risk function for lower respiratory diseases (IHME, 2020). For all mortality results, cause-specific data was taken from the Global Burden of Disease project results for 2019 (IHME, 2020).

Health impact modelling projects the effects of pollutant exposure during the study year. Some health impacts are immediate, such as exacerbation of asthma symptoms and lost working days, whereas other chronic impacts may have a latency of several years. Concentration-response relationships for emergency room visits for asthma and work absences were based on studies that evaluated daily variations in pollutant concentrations and health outcomes; these relationships were applied to changes in annual average concentrations. An overview of the input data to estimate public health impacts of air pollution is shown in Table 6.

Table 6 – Input parameters and data used in estimating physical health impacts

Age group	Effect	Pollutant	Concentration-response function	Concentration change	No-risk threshold	Reference	Incidence data
1-18	New asthma cases	NO_2	1.26 (1.10 – 1.37)	10 ppb	2 ppb	Khreis et al. (2017)	Achakulwisut et al. (2019)
0-17	Asthma emergency room visits	$PM_{2.5}$	1.025 (1.013 – 1.037)	10 µg/m^3	6 µg/m^3	Zheng et al. (2015)	Anenberg et al. (2018)
18-99	Asthma emergency room visits	$PM_{2.5}$	1.023 (1.015 – 1.031)	10 µg/m^3	6 µg/m^3	Zheng et al. (2015)	Anenberg et al. (2018)
Newborn	Preterm birth	$PM_{2.5}$	1.15 (1.07 – 1.16)	10 µg/m^3	8.8 µg/m^3	Sapkota et al. (2012)	Chawanpaiboon et al. (2018)
20-65	Work absence	$PM_{2.5}$	1.046 (1.039 – 1.053)	10 µg/m^3	N/A	WHO (2013)	EEA (2014)
0-4	Deaths from lower respiratory infections	$PM_{2.5}$	IHME (2020)		5.8 µg/m^3	IHME (2020)	IHME (2020)
25-99	Deaths from non-communicable diseases, disaggregated by cause, and from lower respiratory infections	$PM_{2.5}$	Burnett et al. (2018)		2.4 µg/m^3	Burnett et al. (2018)	IHME (2020)
25-99	Disability caused by diabetes, stroke and chronic respiratory disease	$PM_{2.5}$	IHME (2020)		2.4 µg/m^3	Burnett et al. (2018)	IHME (2020)
25-99	Premature deaths	NO_2	1.02 (1.01 – 1.04)	10 µg/m^3	4.5 µg/m^3	Huangfu & Atkinson. (2020); NRT	IHME (2020)

						from Stieb et al. (2021)	
25-99	Premature deaths	SO_2	1.02 (1.01–1.03)	5 ppb	0.02 ppb	Krewski et al. 2009	IHME 2020

Note: Numeric values in the column ‘Concentration-response function’ refer to odds ratio (OR) corresponding to the increase in concentrations given in the column ‘concentration change’. Literature references indicate the use of a non-linear concentration-response function. No-harm threshold refers to a concentration below which the health impact is not quantified, generally because the studies on which the function is based did not include people with lower exposure levels. Data on concentration-response relationships do not exist for all geographies, so a global risk model is applied to all cities. Incidence data are generally unavailable at the city level so national averages have to be applied.

Air pollution both increases the risk of developing respiratory and cardiovascular diseases, and increases complications from them, significantly lowering the quality of life and economic productivity of people affected, and increasing healthcare costs. Economic losses due to air pollution were calculated using the methods outlined in Myllyvirta et al. (2020). The valuation of deaths was updated to the values derived by Viscusi and Masterman (2017), which are based on labour market data, and pay particular attention to applicability in middle- and low-income countries. The Global Burden of Disease project has quantified the degree of disability caused by each disease into a ‘disability weight’ that can be used to compare the costs of different illnesses. The economic cost of disability and reduced quality of life caused by these diseases and disabilities are assessed based on disability weights, combined with the economic valuation of disability used by the UK environmental regulator DEFRA (Birchby et al., 2019), and adjusted by GNI PPP for Indonesia. The deaths of young children are valued at twice the valuation of adult deaths, following the recommendations of the OECD (2012).

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