# Lethal Power

## How Burning Coal is Killing People in Australia

**Dr. Aidan Farrow, Andreas Anhäuser and Lauri Myllyvirta**
**With a preface from Professor Fiona Stanley AC FAA**

Bayswater coal-burning power station © Dean Sewell

Cover image: A billowing smoke stack © Shutterstock

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Mother and child wearing a face mask to protect from air pollution. © Greenpeace/Lu Guang

# Preface

A curious observation by Danish epidemiologists caught my eye. Far fewer preterm babies are being born during the pandemic year. And not only in Denmark, but in Ireland, other European countries, Canada and the US. Researchers have suggested that mothers resting and partners working at home and providing social support may have lowered stress levels. But another interesting suggestion is that lower levels of air pollution may have had a beneficial effect. Babies born preterm have a higher risk of dying and developing disabilities like cerebral palsy, which seems like yet another compelling reason to address our polluting ways of living.

The 2020 pandemic is exposing many aspects of the ways we live on this planet and should raise questions about the wisdom of "snapping back" to "normal". It is now obvious that the "normal" of pre-Covid was damaging to the lives and wellbeing of people, in a variety of ways.  The most clear cut, scientifically studied and worrying challenge facing humankind is climate change. It is and will be far more damaging to us than the pandemic. Politicians and others in power ignored the science around the causes and impact of climate change, even after the devastating bushfires. Perhaps this virus will make them realise that science should be guiding our decisions on such big and complex issues.

In addition to the impact of climate change on global weather patterns, warming, catastrophic bushfires and rising sea levels, there is an immediate and significant impact right here, right now. The adverse impacts of coal-burning power stations on the health of people in Australia, are analysed in detail in this report.

I am an epidemiologist with a long-term commitment to improving the health and wellbeing of pregnant women, children and youth; the evidence is strong that if we create healthy environments early in life (such as not being born preterm), then the positive impacts are lifelong. I have been increasingly anguished and amazed that the health effects of changing climates have been relatively neglected in our responses to these changes. This report shows that they are causing significant illnesses, deaths, costly care and anguish.

Australians need to know that we have 22 active coal-burning power stations, spread across the country from east to west. Whilst most are not in cities they are close enough to them to damage the health of residents. The scarily clear diagrams in this report show how far the particulate matter, nitrogen and sulphur dioxide can travel, with levels way above those considered safe by international standards. And major cities with large populations such as Sydney, Melbourne and Perth with large towns in between have measured unacceptable levels of such pollution. Australians need to know that these coal-burning power stations also emit toxic chemicals, such as mercury, arsenic and lead. I was not aware of the level of these chemicals in pollution from coal power stations. I found these data the most scary: these three all cause brain damage in young children and teenagers whose brains are still vulnerable, particularly mercury and lead. They are known to cause intellectual disabilities and in the most severe exposures, cerebral palsy and birth defects. This vital information needs to get to the decision makers in our state and federal governments whose responsibility it is to enable, not disable, the healthy development of our children. Governments supporting new coal mines and continuing to fund coal burning power stations are writing out prescriptions to maim Australian childrens' brains.

The damaging effects of air pollution from burning coal on the lungs of both children and adults is also described and quantified in this report. Asthma, chronic lung disease


© Prof. Fiona Stanley

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and their effects on other organ systems are all higher with exposure to particulate air pollution. These effects are over and above those in coal miners themselves, with black lung still occurring at unacceptable levels. The cost of burning coal on the health system in Australia was assessed to be over $2 billion every year by the Australian Academy of Technological Sciences and Engineering (ATSE) in 2009[1]. This was before the Morwell fire disaster which would have increased this amount considerably.

The data in this report are compelling and build on the already well-established need to phase out coal and encourage the development and use of renewable energy, of which Australia has an abundance. This is the first on a list of urgent recommendations. The report also recommends that we urgently tighten our emission standards, to match the European Emission Directives (Australia is non-compliant). And that in assessing the cost benefits of coal versus other forms of energy, we include costings of the significant health effects of coal. Whilst we have peak health body demands for levels of particulate matter, the report recommends that these be implemented and that more data are collected on nitrogen and sulphur dioxide and their effects on health outcomes.

The last 200 years is littered with the stories of industries damaging the health of the people, from the cotton mills of Lancashire, child chimney sweeps in London, asbestos (everywhere) to mercury in Minamata, Japan. There is not one example of industries caring for the people, preventing exposures or compensating the victims in a timely fashion. The burning of coal is our biggest global health disaster. Martin Luther King said on receiving the Nobel Peace Prize in 1964, “We have allowed the means by which we live to outdistance the ends for which we live. We have guided missiles and misguided men”. We must continue to fight for our health, and that of our children and their children and convince the misguided men to respond to this report.

Coal-burning power station Hunter Valley, NSW
© Greenpeace/Sewell

# Executive summary

Much of Australia's population is in the grip of an air pollution crisis caused by emissions from coal-burning power stations. In the present study, we find that due to this toxic pollution, hundreds of Australians die every year, and even more suffer from other severe health impacts throughout their lives. We estimate that each year, air pollution from coal-burning power stations is responsible for 800 premature deaths, 850 cases of low birth weight in newborns and 14,000 asthma attacks in children and young adults aged 5-19. The death toll is eight times greater than the average annual casualty number from all natural disasters combined, and still twice as high as the exceptionally high number of deaths in the recent 2019/2020 bushfire season attributed to smoke inhalation.

## Air pollution from coal-burning power stations and its harm to human health

Air pollution has serious impacts on human health. Worldwide, it is responsible for 7 million deaths each year, making it the number one environmental health risk.[2] Coal-burning power stations emit a large range of harmful substances, including nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$) and fine particles ($PM_{2.5}$), which stay airborne for a long time and can travel hundreds of kilometers from the emitting source to surrounding populated areas. Coal burning is also a key source of the toxic heavy metals mercury (Hg), arsenic (As) and lead (Pb). The rate at which mercury is deposited from the atmosphere into the ground has risen dramatically since the industrial revolution world wide.

## Modelling air pollution

Australia still operates twenty-two coal-burning power stations and, despite being a developed country, some of these are among the oldest and most polluting in the world. This report uses an atmospheric dispersion model to estimate near-surface pollutant concentrations resulting from Australia's coal-burning power stations which operate in five groups near Brisbane, Melbourne, Perth, Rockhampton and Sydney. We find that the pollution from the coal-burning power station worsens air quality over large areas spanning hundreds of kilometres, travelling far beyond the immediate vicinity of the power stations themselves. While communities closest to the power stations - mostly rural - suffer the greatest per capita effects, large population centres also experience considerable pollution from the power stations.

In addition to air pollutant concentrations this report also estimates deposition of the potent neurotoxin mercury. Our model results show that mercury deposition rates in some areas affected by the coal-burning power stations are double the already high modern background deposition rate and exceed the pre-industrial natural background rate by orders of magnitude.

## Modelling the health impact of air pollution

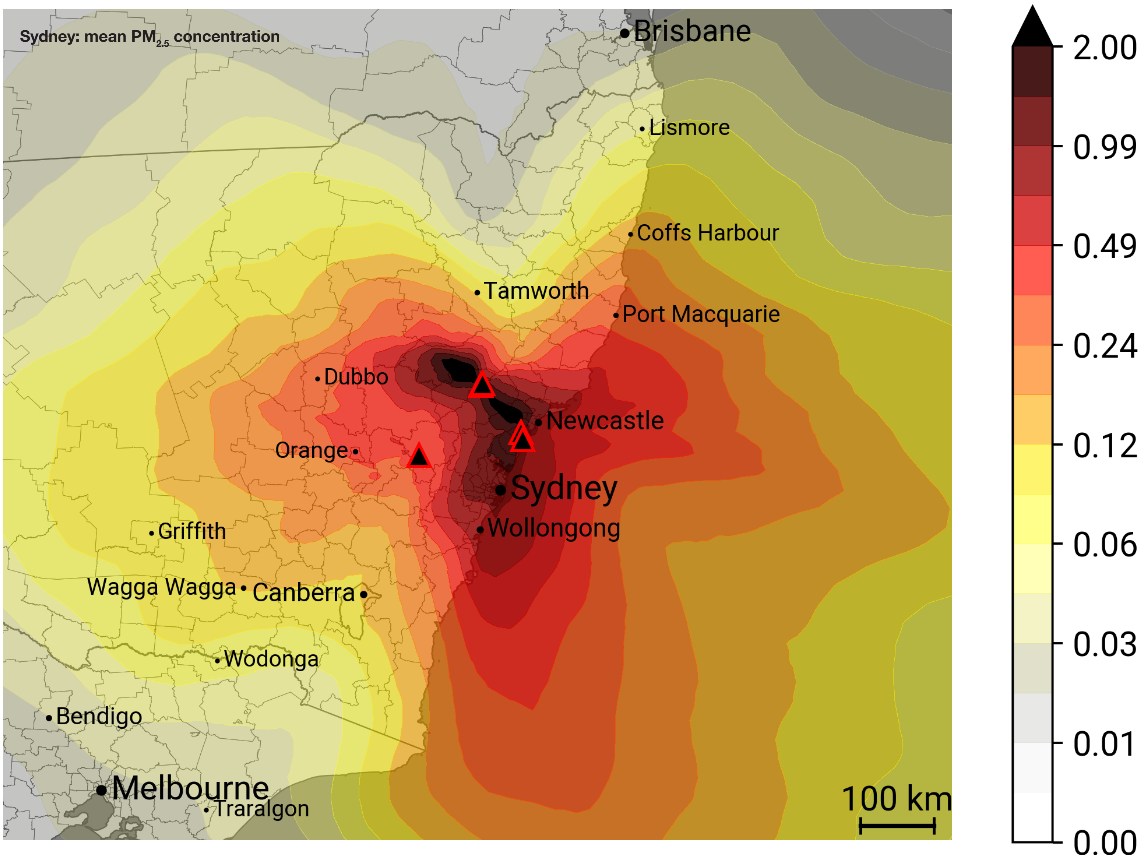
This report applies the modelled pollutant concentrations to a widely used health impact assessment method[3,4,5] to quantify the ways in which pollution from the power stations affects the health of Australians across the country. Our findings reveal the vast extent to which $NO_2$ and $PM_{2.5}$ emissions from coal-burning power stations affect Australians' health from birth to death.

The negative impact of air pollution on human health starts in the womb. Babies born with low birth weight are at increased risk of serious health conditions as adults, including cardiovascular diseases, high blood pressure, type 2 diabetes, and they have an increased risk of premature death. Our model results show that emissions from Australian coal-burning power stations are likely to be responsible for around 850 cases of low birth weight per year. These effects do not stop at state borders: Up to 22% of cases occur in states and territories that are not home to the source of the emissions.

We estimate that around 14,000 additional person-days with asthma symptoms[6] suffered by children and teenagers in Australia each year are attributable to emissions from coal-burning power stations.

Around 800 premature deaths per year are found to be attributable to pollution from coal-burning power stations. As with other impacts, some of these deaths occur in regions far away from the emitting coal stations.

Depending on the wind direction and speed, $PM_{2.5}$ emitted from the coal-burning power station group near Sydney can travel all the way up to the Gold Coast in South-East Queensland and down to Shepparton in regional Victoria. Populations living closest to the power stations, such as Sydney, Singleton and Newcastle, are at greatest risk of exposure.



## Air pollution and SARS-CoV-2 / COVID-19

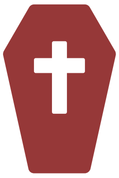
The link between air pollution and COVID-19 is not studied in depth in this report. However, there is strong evidence that exposure to air pollution increases both the risk of infection with the SARS-CoV-2 virus, as well as the severity and mortality of the associated COVID-19 disease.[7] Therefore, air pollution must be considered as a modifiable risk factor in the coronavirus pandemic and we expect that addressing the sources of air pollution (such as poorly regulated coal-burning power stations) would not only reduce the large burden of 'ordinary' health impacts studied in this report but also lower the risk posed by the ongoing COVID-19 outbreak.

## Recommendations

The health impacts outlined in this report make clear that Australia's regulation of coal-burning power stations has failed. The additional costs to future generations around the globe due to the emission of long-lived greenhouse gases are not considered in this report. In light of the availability of cheaper and much cleaner alternatives for electricity generation,[8] Where is no justification for developing or operating coal-burning power stations in Australia. Those that are already in operation must be closed in the shortest possible time and any that continue to operate must be urgently retrofitted with the best available emission reduction technology.

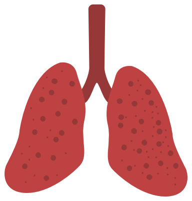
**To deal with this crisis, Greenpeace Australia Pacific makes the following recommendations to state governments:**

- Develop a plan to ensure coal is completely phased out and replaced with renewable energy in the shortest possible time, with regional plans to prepare communities for economic adjustment.
- Significantly tighten emission limits in existing power stations equivalent to the lower atmospheric emission limit described by the European Industrial Emission Directive best available technique conclusions, until their closure.
- Ensure any load-based licensing or pollution fee schemes reflect the damage to human health and costs to the healthcare system caused by air pollution, to ensure these costs are no longer externalised by electricity generators.
- Conduct independent health-risk assessments for major sources of air pollution to ensure air pollution policy reflects the best available public health evidence.
- Adopt the advice of peak health organisations on the appropriate science-based values for ambient air quality standards for sulfur dioxide, nitrogen dioxide and ozone.
- Ratify and implement the Minamata convention, the International treaty on mercury emission reduction.



**785**

**people die from exposure to pollution from burning coal every year in Australia**

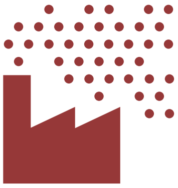


**14,456**

**asthma symptoms are suffered by children due to air pollution from burning coal every year in Australia**

**845**

**babies are born prematurely due to pollution from burning coal every year in Australia**



**22**

**coal-burning power stations still operate in Australia some of which are among the oldest and most polluting in the world**

# 1.0 Introduction

Toxic air pollution from coal-burning power stations in Australia poses serious risks to human health. Our model results show that it is responsible for around 14,000 annual incidences of asthma attacks[9] in children and young adults aged 5-19, 850 cases of low birth weight, and 800 premature deaths a year.

Australia has some of the oldest and most polluting coal-burning power stations in the world. Ten Australian coal-burning power stations have closed since 2012. Most of the remaining twenty-two are operating significantly beyond their intended design lives.[10] Declining costs of renewable energy and a growing awareness that rapid reduction in greenhouse gas emissions is needed mean that it is unlikely that another coal-burning power station will be built in Australia without massive government subsidies. However, the timing of coal station closures has dramatic implications for the health of the Australian population: the longer we wait, the more people are at risk of damaged health or premature death.

Coal-burning power stations emit pollutants including particulate matter ($PM_{2.5}$ and $PM_{10}$), sulfur dioxide ($SO_2$), nitrogen oxides (NOx), mercury, lead and arsenic into the air (see Box 1). Directly emitted pollutants also contribute to the formation of secondary pollutants through chemical reactions in the atmosphere. These include ground-level ozone and secondary particulate matter. Greenpeace analysis of data from the National Pollutant Inventory finds that AGL, Origin Energy and Energy Australia account for 36.5% of $PM_{2.5}$, 40.5% of sulfur dioxide, 40.5% of all nitrogen dioxide and 46.1% of all mercury from coal-burning power stations in Australia.[11]

Child suffering from asthma
© Greenpeace

**Box 1: Air Pollutants**

$PM_{2.5}$

**Fine particulate matter ($PM_{2.5}$)**

*Fine particulate matter* or *fine particles* ($PM_{2.5}$) are solid particles smaller than 2.5µm.[12] $PM_{2.5}$ is a dangerous air pollutant which - due to its small size - can pass deep into lungs, hearts and veins, infiltrating every part of the human body. Chronic exposure to $PM_{2.5}$ increases the risk of cardiovascular and respiratory diseases, as well as of lung cancer. There is no level of fine particle pollution that is known to be safe.[13]

$SO_2$

**Sulfur dioxide ($SO_2$)**

$SO_2$ is a gaseous pollutant emitted by natural and anthropogenic activities including burning fossil fuels, especially coal. There is strong evidence of negative health impacts resulting from exposure to $SO_2$, including respiratory conditions such as chronic obstructive pulmonary disorder[14,15], bronchitis[16] and non-communicable diseases such as stroke[17,18], cardiovascular disease[19] and (via particulates) lung cancer.[20]

$NO_x$

**Nitrogen oxides ($NO_x$)**

When coal is burned in air, ***nitrogen oxides*** (NO and $NO_2$; short $NO_x$) are created from the molecular nitrogen ($N_2$), which makes up 78% of the atmosphere, and from any nitrogen contained in the fuel. Nitrogen oxides have numerous impacts on human health, notably on the cardiovascular system and respiratory system, and they exacerbate symptoms of asthma, chronic obstructive pulmonary disorder, and other respiratory diseases.[21,22]

$O_3$

**Ozone ($O_3$)**

*Ozone* in the higher atmosphere (the ***stratosphere***) protects the Earth's surface from dangerous ultraviolet radiation from the sun. But when present in the lower atmosphere at near-ground level, it is an air pollutant that causes smog. Ground level ozone is a secondary pollutant. It is not directly emitted by power stations but forms when $NO_x$ pollution reacts with other chemicals in the atmosphere. The health impacts of ozone pollution include chest pain, throat irritation and inflammation of the airways, impaired lung function and increased symptoms of bronchitis, emphysema and asthma. Ozone can increase susceptibility to infections.[23]

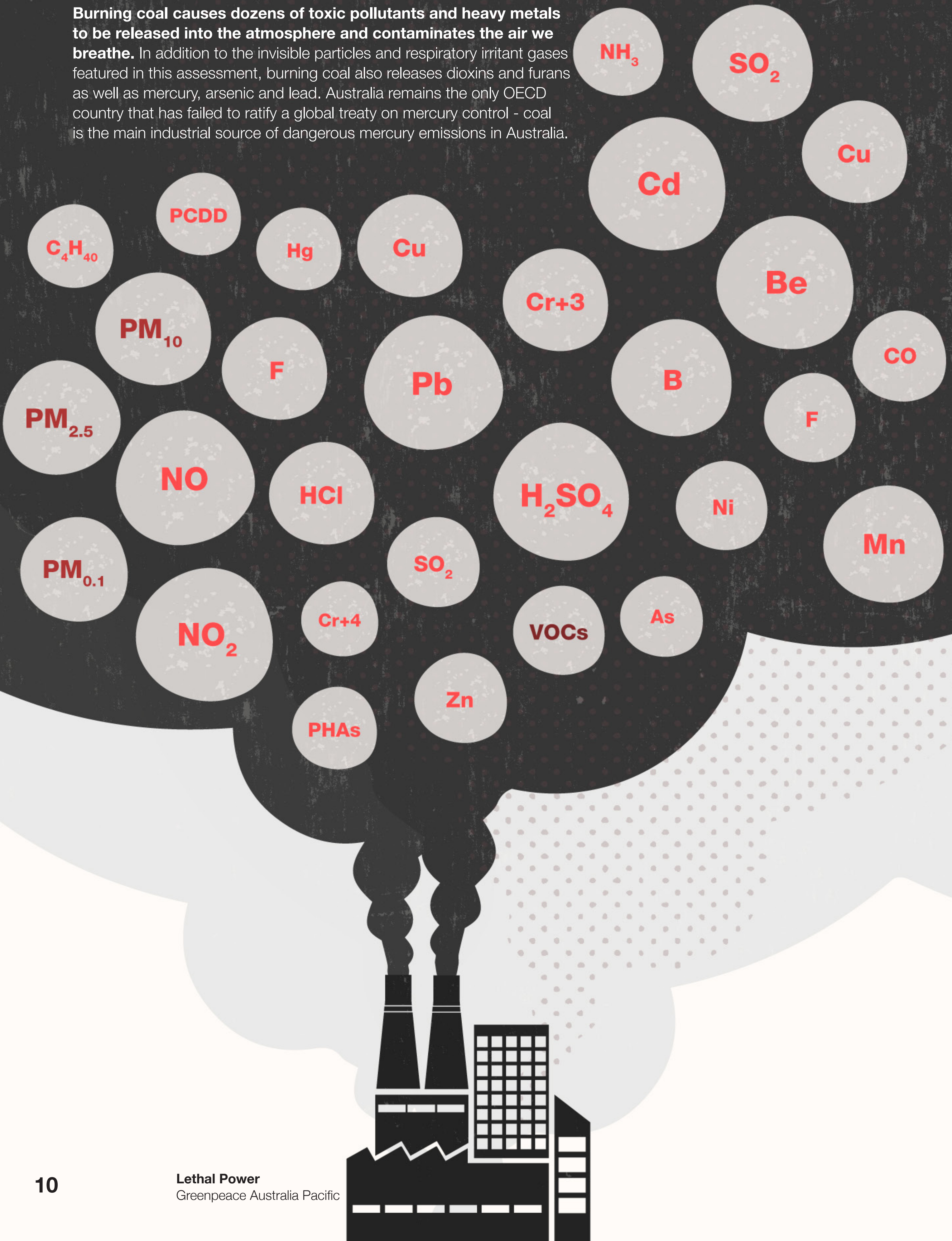
Hg

**Mercury (Hg)**

*Mercury* is a potent neurotoxin that can cause severe health problems, even at very low doses, and poses serious risks to the cognitive and neurological development of children. The WHO considers mercury to be one of the top ten chemicals of major public health concern.[24] Coal burning is a key source of mercury discharge into the environment globally.[25] Once in the environment, mercury is a persistent pollutant. It does not usually arrive in the human body directly but rather through ingestion of contaminated food, particularly seafood.

# Coal power station air pollution

**Burning coal causes dozens of toxic pollutants and heavy metals to be released into the atmosphere and contaminates the air we breathe.** In addition to the invisible particles and respiratory irritant gases featured in this assessment, burning coal also releases dioxins and furans as well as mercury, arsenic and lead. Australia remains the only OECD country that has failed to ratify a global treaty on mercury control - coal is the main industrial source of dangerous mercury emissions in Australia.



Air pollution affects physical and mental health. Exposure to an air pollutant or combination of air pollutants, such as the pollutants emitted by coal-burning power stations, is associated with increased incidence of many diseases including ischaemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer, lower respiratory infections, premature birth (preterm birth), type II diabetes, stroke and asthma. Vulnerable groups such as children, elderly people, and those with pre-existing respiratory ailments are at heightened risk.[26,27,28,29]

Coal pollution is not a problem isolated to the communities that live in the immediate vicinity of a coal-burning power station. Air pollution can travel for hundreds of kilometres, affecting expanding urban populations, we investigate the effects on communities in the Hunter Valley (New South Wales), Latrobe Valley (Victoria), Collie River Valley (Western Australia) and Central Queensland.

This report quantifies the health impacts of some of the most dangerous substances that make up the toxic pollution produced by coal-burning power stations and offers practical recommendations for how to deal with the problem.

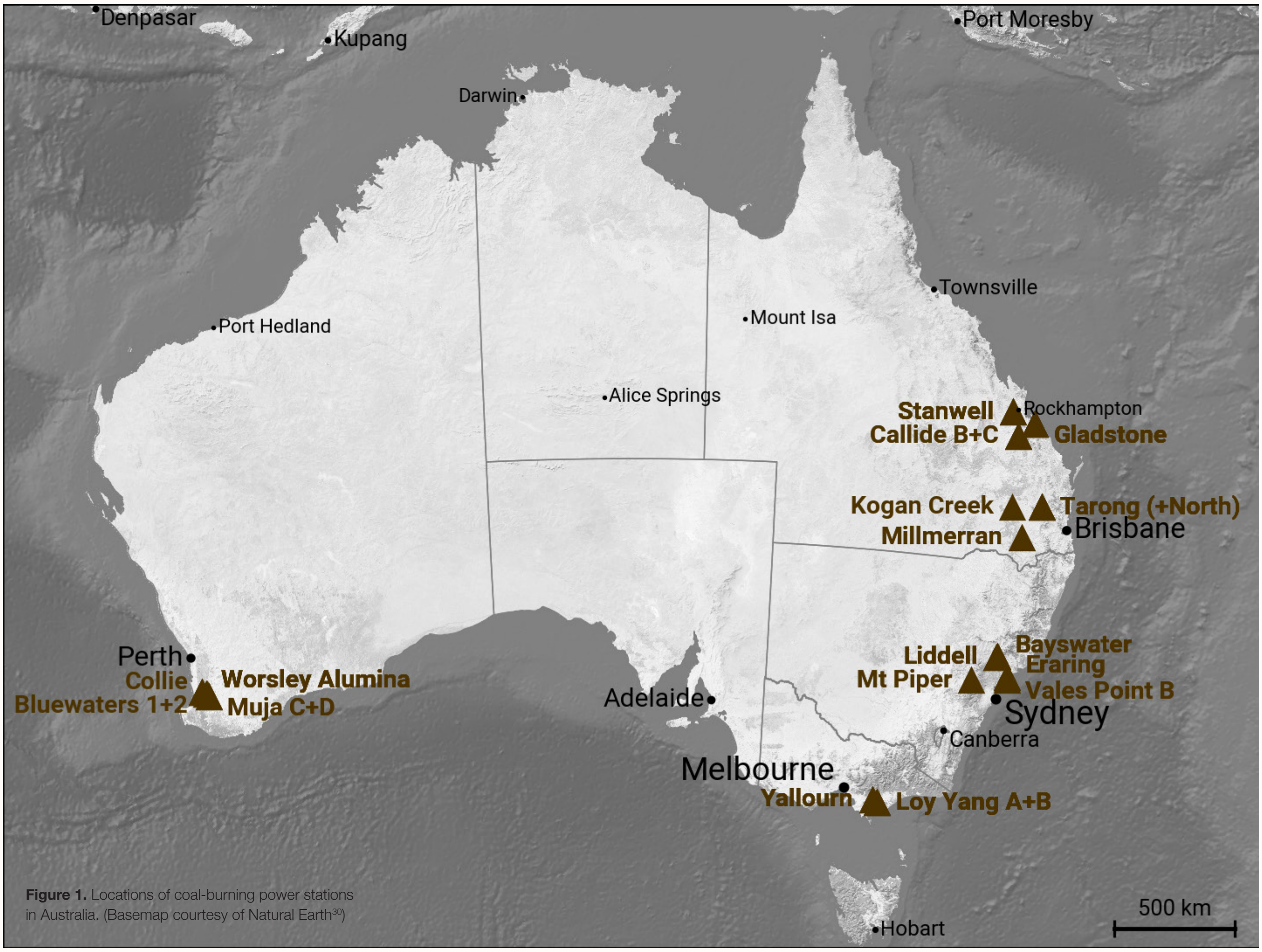


**Figure 1.** Locations of coal-burning power stations in Australia. (Basemap courtesy of Natural Earth[30])

# 2.0 Modelling emissions and health impacts

This section provides a technical description of the modelling system used to obtain our results which are presented in Section 3. Further details are found in Appendix. A number of technical terms are explained in the Glossary.

The health impact assessment employed here follows two stages. An atmospheric dispersion model is used to estimate the coal-burning power stations' contribution to near-surface pollutant concentrations. The modelled pollutant concentrations provide an estimate of the exposure, that is, the dose experienced by the population. Concentration response factors from the literature that describe empirical relationships between air pollutants and adverse health outcomes are then used to estimate the health impact. Demographic data, including from the latest Australian Census (2016)[31] is used to describe the population at risk, allowing us to quantify the specific impact on the Australian population.

## 2.1 Pollutant Emissions

According to the model employed in this study, the emission of air pollutants from a coal-burning power station are determined by the station's capacity, utilization (load), the coal type used, and the design of the boiler and any emission reducing technology. Typically higher pollutant emissions are associated with lower grade coals (lignite rather than higher grade bituminous coals) and with older or less efficient boiler technology (subcritical rather than supercritical). A typical expected design operation period for a coal-burning power station is 30 years. Of the 22 stations currently operating in Australia, 17 use subcritical boilers and 11 are over 30 years old. The modelled power stations are described in Table 1, and the input parameters for the model, including emissions data, are presented in Appendix A.1.

Yallourn Power Station is a complex of six brown coal-burning power stations in the La Trobe Valley, Victoria.
© Jeremy Buckingham MLC

| Power station | Power station group | Built | Full capacity (MW) | Average load (%) | Coal type | Boiler type |
|---|---|---|---|---|---|---|
| Kogan Creek | Brisbane | 2007 | 750 | 91 | Bituminous | Supercritical |
| Millmerran | Brisbane | 2002 | 852 | 84 | Subbituminous | Supercritical |
| **Tarong** | **Brisbane** | **1984** | **1400** | **65** | **Subbituminous** | **Subcritical** |
| Tarong North | Brisbane | 2002 | 450 | 78 | Subbituminous | Supercritical |
| Loy Yang B | Melbourne | 1993 | 1000 | 93 | Lignite | Subcritical |
| **Loy Yang A** | **Melbourne** | **1985** | **2180** | **86** | **Lignite** | **Subcritical** |
| **Yallourn Power Station** | **Melbourne** | **1974** | **1450** | **74** | **Lignite** | **Subcritical** |
| Bluewaters | Perth | 2008 | 217 | 76 | Subbituminous | Subcritical |
| Bluewaters 2 | Perth | 2009 | 217 | 76 | Subbituminous | Subcritical |
| Collie | Perth | 1999 | 318 | 59 | Subbituminous | Subcritical |
| **Muja-C** | **Perth** | **1981** | **389** | **53** | **Subbituminous** | **Subcritical** |
| **Muja-D** | **Perth** | **1986** | **425** | **47** | **Subbituminous** | **Subcritical** |
| **Worsley Alumina** | **Perth** | **1982** | **216** | **n/a** | **Bituminous** | **Subcritical** |
| Callide B | Rockhampton | n/a | 700 | 79 | n/a | n/a |
| Callide C | Rockhampton | 2001 | 810 | 88 | Subbituminous | Supercritical |
| **Gladstone** | **Rockhampton** | **1976** | **1680** | **61** | **Bituminous** | **Subcritical** |
| Stanwell | Rockhampton | 1993 | 1460 | 64 | Subbituminous | Subcritical |
| **Bayswater** | **Sydney** | **1982** | **2640** | **63** | **Bituminous** | **Subcritical** |
| **Eraring** | **Sydney** | **1982** | **2880** | **70** | **Bituminous** | **Subcritical** |
| **Liddell** | **Sydney** | **1971** | **2000** | **58** | **Bituminous** | **Subcritical** |
| Mt Piper | Sydney | 1993 | 1400 | 71 | Bituminous | Subcritical |
| **Vales Point B** | **Sydney** | **1978** | **1320** | **66** | **Bituminous** | **Subcritical** |

**Table 1.** Overview of Australian coal-burning power stations. Stations operating for over 30 years are shown in bold, data sources provided in Appendix A.1. Technical terms are explained in the glossary.

## 2.2 Atmospheric Dispersion Modelling

The atmospheric dispersion model includes a meteorology module and a chemistry-transport module.

- **Meteorology module.** We use version 3 of the *The Air Pollution Model* (TAPM)[32] to calculate hourly meteorological conditions across a gridded model domain around the power stations. Although TAPM includes the ability to model pollutant dispersion, only its meteorology component is used. A more sophisticated chemistry-transport model is used to assess pollutant dispersion (see below). Around each of the power station groups TAPM is run on three nested domains with spatial resolutions of 30 km, 10 km and 5 km, respectively, getting finer towards the center (Figure 2). Boundary conditions for the meteorology simulation are derived from the GASP model data of the Australian Bureau of Meteorology.[33] In each simulation, the model is run for the whole year of 2018 with a 12 day spin-up period comprising the last 12 days of 2017. Only the 2018 data are used in the analysis.

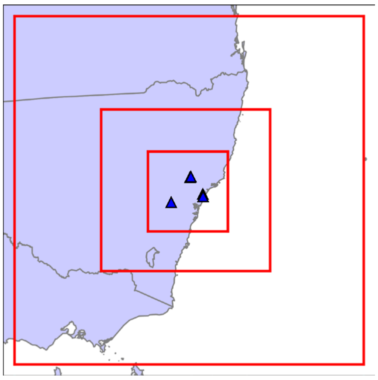


**Figure 2:** A numerical weather model with three nested domains (red boxes) around the modelled power stations (blue triangles) is run for each of the power station groups (here Sydney).

- **Chemistry-transport module.** The atmospheric dispersion, chemical transformation and deposition of the power station emissions are modelled using version 7 of CALPUFF.[34] To isolate the impact of coal-burning power stations in this work, no boundary fluxes or emission sources other than the studied power stations are included in the model. No consideration is given to air pollution sources from other parts of the coal supply chain - such as mining, hauling, storage, coal ash disposal - or from other sources such as transport and industry. We include power station emissions of mercury (elemental, divalent and particle-bound), NO, $NO_2$, $SO_2$ and primary $PM_{2.5}$. Background concentrations of ozone ($O_3$), ammonia ($NH_3$) and hydrogen peroxide ($H_2O_2$) are included for use by the chemistry module. Chemical transformations of sulfur and nitrogen species are modelled using the ISORROPIA (gas-particle equilibrium $NH_3$, $H_2SO_4$, and $HNO_3$) and RIVAD ($SO_2$ to $SO_4$ and NO/$NO_2$ to $HNO_3$ and $NO_3$) chemistry modules within CALPUFF. The chemical reaction set requires background pollutant concentrations of ozone ($O_3$), ammonia ($NH_3$) and hydrogen peroxide ($H_2O_2$). These are obtained from Geos-Chem global benchmark simulations.[35] The model outputs an hourly time series of near-surface concentrations of the pollutants and the deposition of mercury at gridded receptor locations across the model domains.

  CALPUFF is run for the whole year with static emission rates representing 100% utilisation of all of coal-burning power stations. Real world emissions from the power stations are time varying and power station capacity is in general not fully utilised (Table 1, see also Appendix A.1 for details). The resulting hourly ground-level pollutant concentration fields therefore represent a worst-case scenario. For the purposes of health impact assessment we only used annual average concentrations, which have been adjusted for real world utilization. Adjustment has been done with a scaling factor representing each station's load during 2018. This effectively spreads the station's annual emissions volume evenly through the year. All annual mean values presented in this report are adjusted in this way, and the explicit mention of this word will be omitted henceforth.

The modelled power station geometry and emissions parameters are provided in Appendix A1.

## 2.3 Health impact assessment

The annual average concentration values are the pollution that is attributable to emissions from the power stations alone. We call this the *excess pollution* (in excess of the hypothetical pollution level in the absence of the power stations). By applying a widely used health impact assessment method[36,37,38] to the average concentrations of $NO_2$, $SO_2$ and $PM_{2.5}$, we quantified the ways in which pollution from the power stations affects people's health in various stages of their lifetime. We assess low birth weight, asthma symptoms suffered by children and teenagers and premature mortality. In each assessment we quantify uncertainty in terms of a *best* estimate and a surrounding 95%-confidence interval, the bounds of which we term the *low* and *high estimates.*

To assess the population-specific health impact for the Australian population we use the 1-km resolution global population data for 2010 from the Socioeconomic Data and Applications Center (SEDAC).[39] As Australia's population has grown by approximately 14% since 2010,[40] the estimation of the total health impact may therefore be underestimated. The latest Australian Census (2016)[41] is used to create data for specific age groups and birth numbers. For each of the *State Suburbs* divisions, we multiplied the SEDAC population count on each point that lies within that division by the ratio of people in this age group (or birth number) over the total population in this domain computed from the *Selected Person Characteristics* of the census data.

The impact assessments require data describing the background health of the Australian population. Background death rates for various causes are taken from the Australian Bureau of Statistics' count for 2018.[42,43]

We determine the subset of the Australian population who have asthma by multiplying the values of the appropriate age group population by the gender-averaged fraction of people with asthma in Australia as found by the 2017 Australian National Health Survey (NHS).

The background rate of asthma symptoms has been retrieved through the ABS Table Builder tool by scaling up the value for "Number of times asthma interfered with daily activities in last 4 weeks"[44] of 5-19 year old people with asthma to a full year.[45]

To get a spatially resolved absolute number for low weight births, we multiply the spatially resolved absolute birth numbers with the latest available data (2010)[46] for low birth weight prevalence rate (fraction of total births) for Australia, from the World Bank's World Development Indicators.[47] In that dataset, low birth weight is defined as occurring if the newborn weighs less than 2,500 grams, measured within the first hour of their life.[48]

The incidence of a health outcome caused by the excess pollution is estimated using empirical values of *relative risks* relating negative health outcomes (asthma symptoms, low birth weight, death) to increases in pollutant concentrations. The relative risk $r$ expresses how much more likely an individual is to experience that health outcome if they are exposed to a certain excess pollution compared to if they were not exposed:

$$m_x / m_0 = r \qquad (1)$$

where $m_x$ is the incidence rate under the excess pollution $\Delta x$, and $m_0$ is the incidence rate in absence of the excess pxollution. The incidence rate is the number of cases where an individual experiences this health outcome divided by the relevant population. The relevant population groups are those 'at risk' of the outcome in question (children with asthma, newborns, total population) over a specified length of time (in most cases a year). In state-of-the-art epidemiological models, $\boldsymbol{r}$ depends exponentially on $\boldsymbol{x}$ for $m_x << 1$:[49,50]

$$r = \exp(c\ \Delta x) \qquad (2)$$

with **c** being a constant commonly called *concentration response* (or *dose-response) factor.* The concentration response factors are computed from relative risks given by the sources listed in Table 2. Combining Eqs. (1) and (2) gives

$$m_x = m_0 \exp(c\, \Delta x)$$

Since the number of cases over a given year is the number of the relevant population group $P$ times the incidence rate, the number of cases under the higher pollutant concentration is

$$d_x = P\, m_0 \exp(c\, \Delta x)$$

The number of cases attributable to the excess pollution (defined as pollution from the power stations) is

$$\Delta d = d_x - d_0 = P\, m_0 \,[\exp(c\, \Delta x) - 1]$$

Integrating $\Delta d$ spatially over the model domain gives the total number of cases attributable to the excess pollution within the model domain. Where health impacts are apportioned to regions or states, administrative domain borders are taken as defined in version 3.6 (May 2018) of the GADM project.[51]

The authors of the source from which we retrieved the relative risk of $NO_2$-caused deaths (Table 2) note that “up to 33%” of these deaths “may” overlap with cases due to $PM_{2.5}$ exposure.[52] They give no lower bound for this overlap. Our interpretation of this statement is that the actual overlap is somewhere in the interval [0%..33%].[53] As we have no information which of these values is most probable to be true, we assume uniform probability for all values in the interval. In order to avoid double counting, we have accounted for this (potential) overlap by modifying the raw number of $NO_2$-caused deaths after applying the concentration response factors in the following way:

- The low estimate of the $NO_2$-caused deaths is reduced by 33% (the maximum possible overlap).
- The high estimate of the $NO_2$-caused deaths is left unchanged because the lowest possible overlap is zero.
- The best estimate of the $NO_2$-caused deaths is reduced by 16.5%, the central value of the possible overlap interval (in mathematical terms, the expected value of the overlap). With the available information, this appears to be the natural assumption.

We believe that this approach best reflects what is meant by the estimates. [54] All numbers for $NO_2$-caused deaths that are shown in this report have already been adjusted in this way.

Hazelwood, operated by French utility Engie in the Latrobe Valley, was the dirtiest power station in the developed world until its closure.
© Jeremy Buckingham MLC

| Population | Outcome | Pollutant | Pollutant statistics | Source | RR at 10μg/m$^3$ increase (95%-confidence interval) | | |
|---|---|---|---|---|---|---|---|
| | | | | | **Best estimate** | **Low estimate** | **High estimate** |
| Newborns[55] | Low birth weight[56] | $PM_{2.5}$ | Annual mean | ESCAPE (2013)[57] | 1.988 | 1.440 | 2.723 |
| People with asthma aged 5-19 | Days with asthma symptoms | $PM_{10}$ | Daily mean | HRAPIE (2013)[58] | 1.028 | 1.006 | 1.051 |
| Aged 30+ | Death (all causes) | $NO_2$ | Annual mean | HRAPIE (2013) | 1.055 | 1.031 | 1.080 |
| All | Death (ALRI) | $PM_{2.5}$ | Annual mean | Mehta et al. (2011)[59] | 1.12 | 1.03 | 1.30 |
| All | Death (lung cancer) | $PM_{2.5}$ | Annual mean | Krewski et al. (2009)[60] | 1.142 | 1.057 | 1.234 |
| All | Death (heart failure) | $PM_{2.5}$ | Annual mean | Pope et al. (2015)[61] | 1.028 | 1.006 | 1.051 |
| All | Death (diabetes) | $PM_{2.5}$ | Annual mean | Pope et al. (2015) | 1.13 | 1.02 | 1.26 |
| All | Death (stroke) | $PM_{2.5}$ | Annual mean | Pope et al. (2015) | 1.128 | 1.077 | 1.182 |
| All | Death (IHD) | $PM_{2.5}$ | Annual mean | Pope et al. (2015) | 1.287 | 1.177 | 1.407 |

**Table 2.** Data sources for relative risks (RR).

Bayswater coal-burning power station
© Greenpeace/Sewell

# 3.0 Results

## 3.1 Air pollutant concentrations

Our model results show how pollutants emitted by the Sydney, Melbourne, Brisbane, Perth, and Rockhampton coal-burning power station groups affect air quality over areas spanning hundreds of kilometres and affecting millions of Australians. Both rural communities and urban areas are affected.

The annual average $PM_{2.5}$ pollution from each of the modelled power station groups include both primary $PM_{2.5}$ pollution and secondary $PM_{2.5}$ pollution (Figures 3-7). The model results only include pollutant emissions arising from the included coal-burning power stations; no other natural or anthropogenic sources of air pollution are accounted for. The results presented therefore do not represent the full burden of air pollution experienced by Australians.

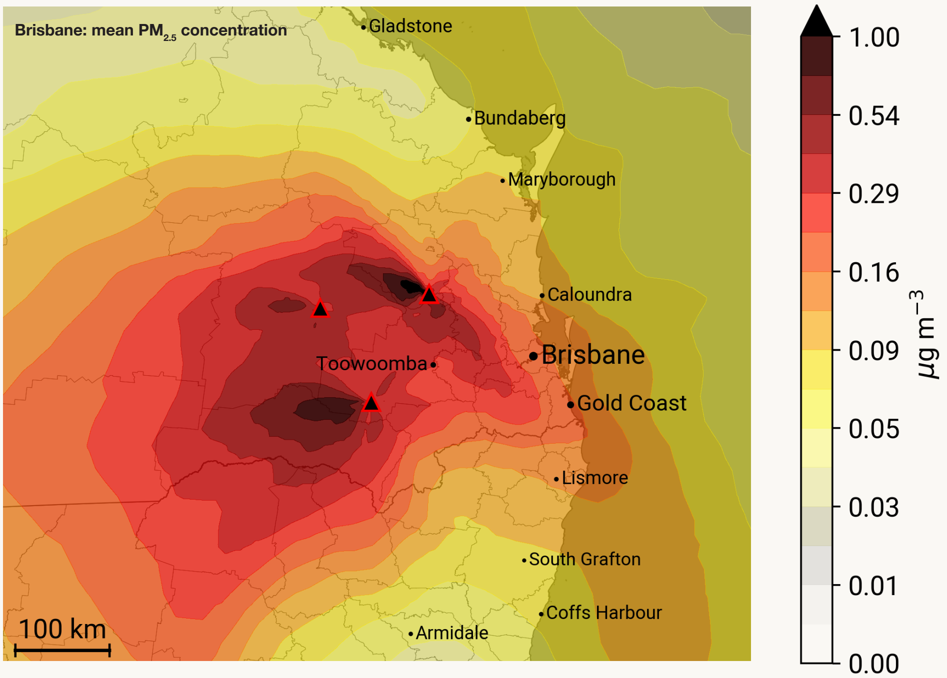


**Figure 3.** Annual mean near-surface $PM_{2.5}$ concentration due to emissions by the Brisbane power station group.

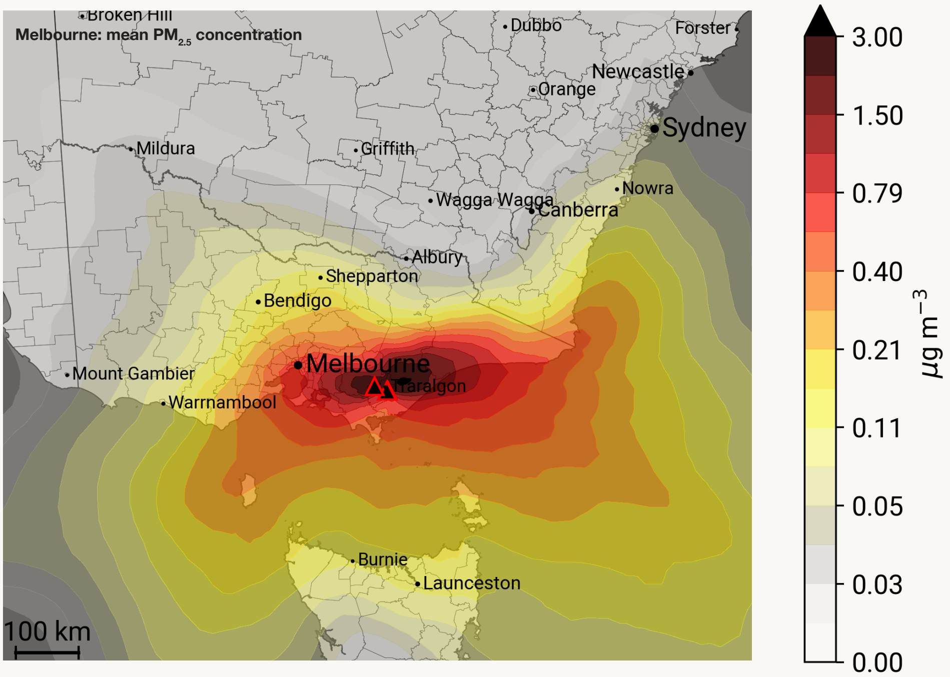


**Figure 4.** Annual mean near-surface $PM_{2.5}$ concentration due to emissions by the Melbourne power station group.

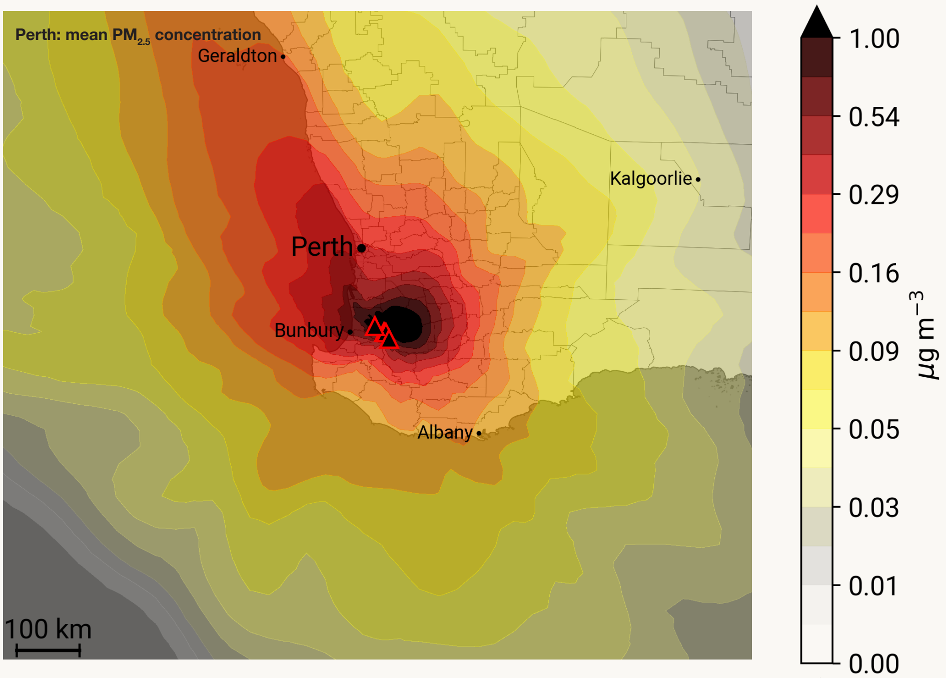


**Figure 5**. Annual mean near-surface PM$_{2.5}$ concentration due to emissions by the Perth power station group.

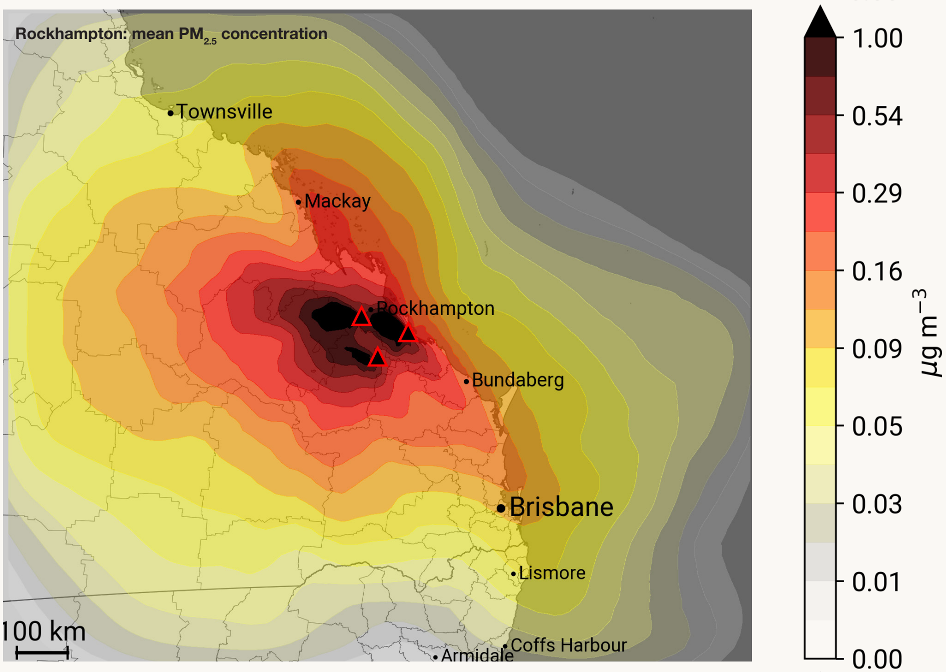


**Figure 6.** Annual mean near-surface PM$_{2.5}$ concentration due to emissions by the Rockhampton power station group.

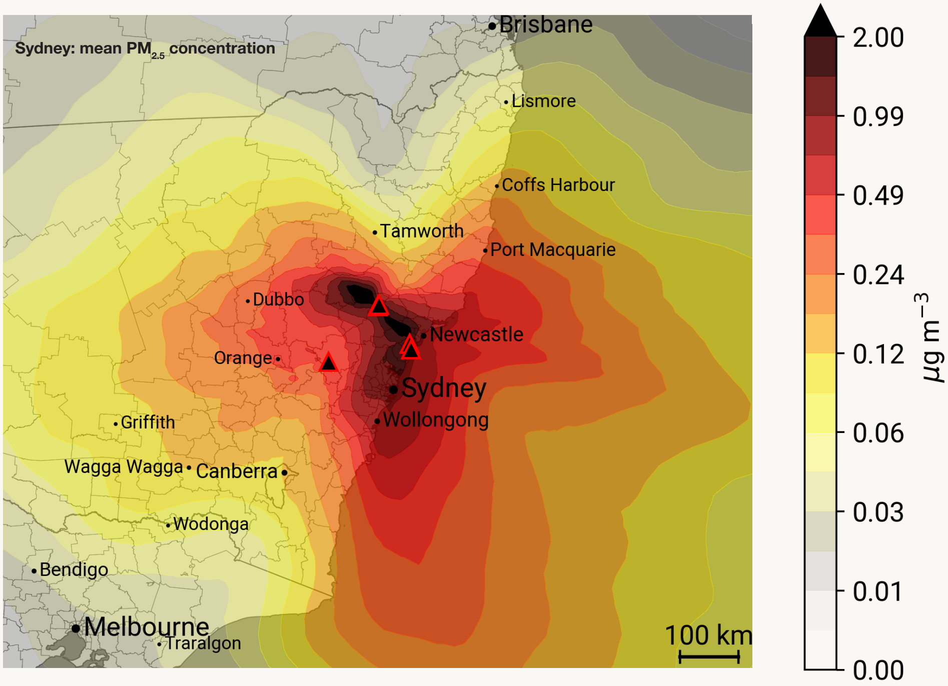


**Figure 7.** Annual mean near-surface PM$_{2.5}$ concentration due to emissions by the Sydney power station group.

## 3.2. Mercury deposition

World wide, the rate that mercury is deposited from the atmosphere has risen dramatically since the industrial revolution such that background deposition rates are many times the natural rate. The pre-industrial mercury atmospheric deposition rate is estimated to have been as low as 1 µg/m²/year,[62] while modern rates are estimated to be around 10 to 20 µg/m²/year.[63,64]Emissions from coal-burning power stations can create significant local hotspots of mercury deposition.[65]

In some locations the modelled annual average power station contribution to mercury deposition rates is as much as 10 µg/m²/year (Figures. 8-12). Given that background deposition rates are of a similar magnitude, our results show that mercury deposition rates in some areas are effectively doubled as a consequence of coal-burning power station emissions. In these locations the combined background and power station contribution to the mercury deposition rate is many times higher than the natural rate.

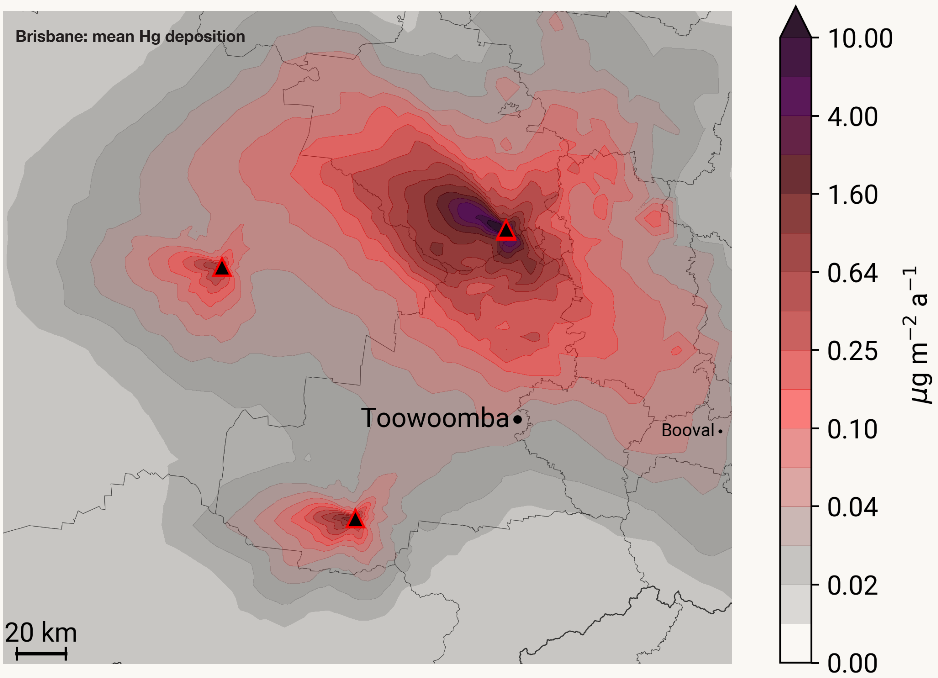


**Figure 8.** Annual mean deposition rate of mercury emitted by the Brisbane power station group.

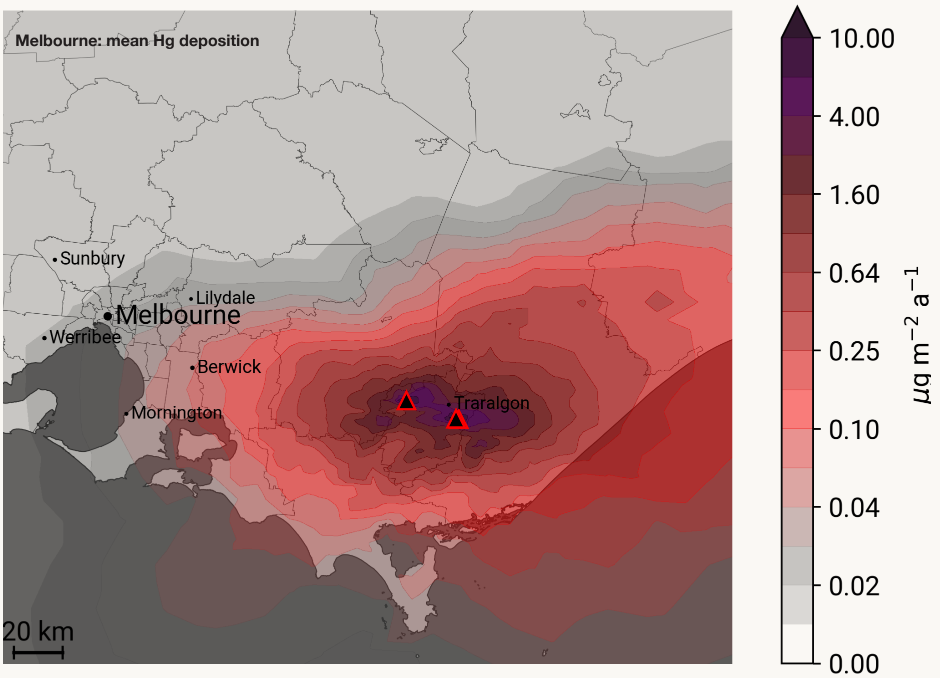


**Figure 9.** Annual mean deposition rate of mercury emitted by the Melbourne power station group.

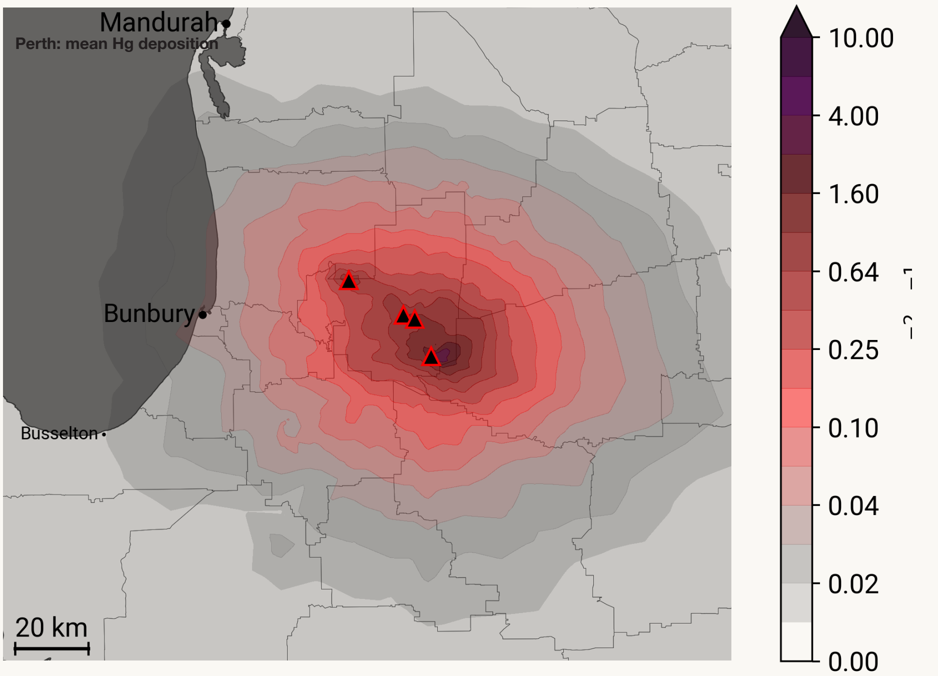


**Figure 10.** Annual mean deposition rate of mercury emitted by the Perth power station group.

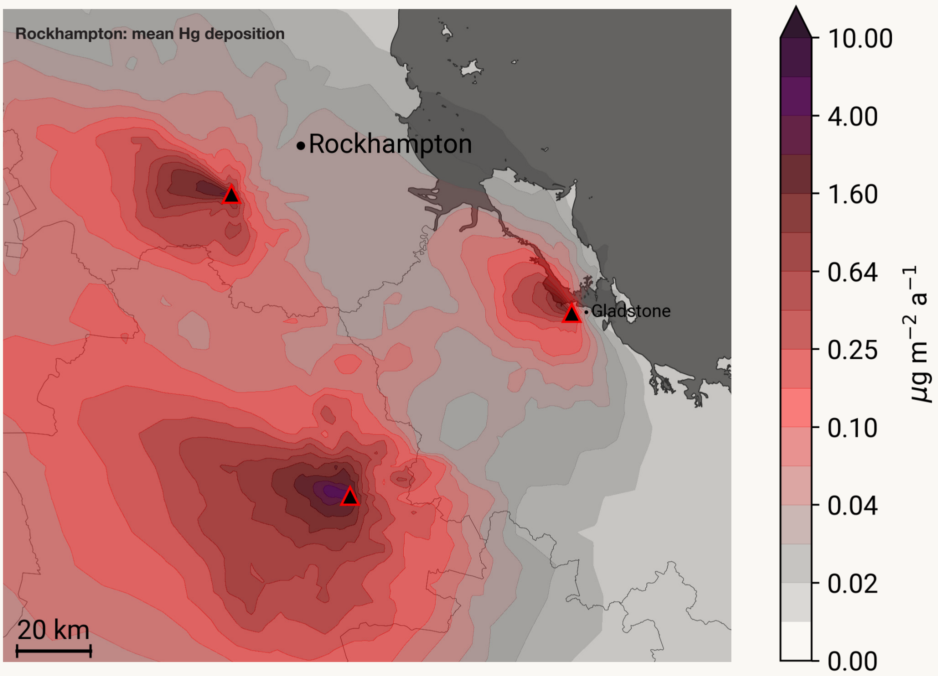


**Figure 11.** Annual mean deposition rate of mercury emitted by the Rockhampton power station group.

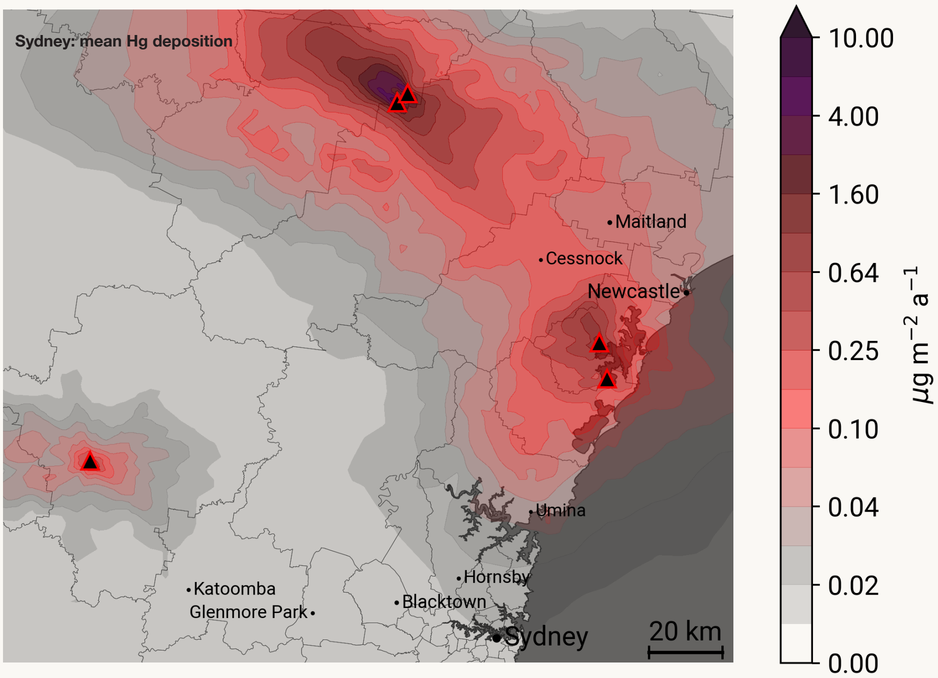


**Figure 12.** Annual mean deposition rate of mercury emitted by the Sydney power station group.

# 3.3 Human health impacts

## 3.3.1 Low birth weight

Long-term exposure to $PM_{2.5}$ pollution during pregnancy has been found to be linked to low birth weight.[66] Babies born with low birthweight are at increased risk of health conditions including cardiovascular diseases, high blood pressure, Type 2 diabetes, and premature mortality.[67] Our model results suggest that the emissions from Australia's coal-burning power stations are responsible for 400 to 1,300 cases of low birth weight each year (Table 3). As the dispersion of the pollution does not stop at political borders, 22% of these cases occur in states and territories that are not host to the emitting power station (Table A2.1 and Table A2.2).

| Low birth weight (total cases per year) | | | |
|---|---|---|---|
| **Power station group** | **95%-confidence interval** | | |
| | **best estimate** | **low estimate** | **high estimate** |
| **Total** | **845** | **439** | **1,253** |
| Brisbane | 55 | 29 | 81 |
| Melbourne | 259 | 134 | 383 |
| Perth | 47 | 24 | 68 |
| Rockhampton | 35 | 18 | 52 |
| Sydney | 450 | 233 | 669 |

**Table 3:** Modelled number of annual cases of low birth weight due to $PM_{2.5}$ pollution from coal-burning power stations in Australia - sums per power station group.

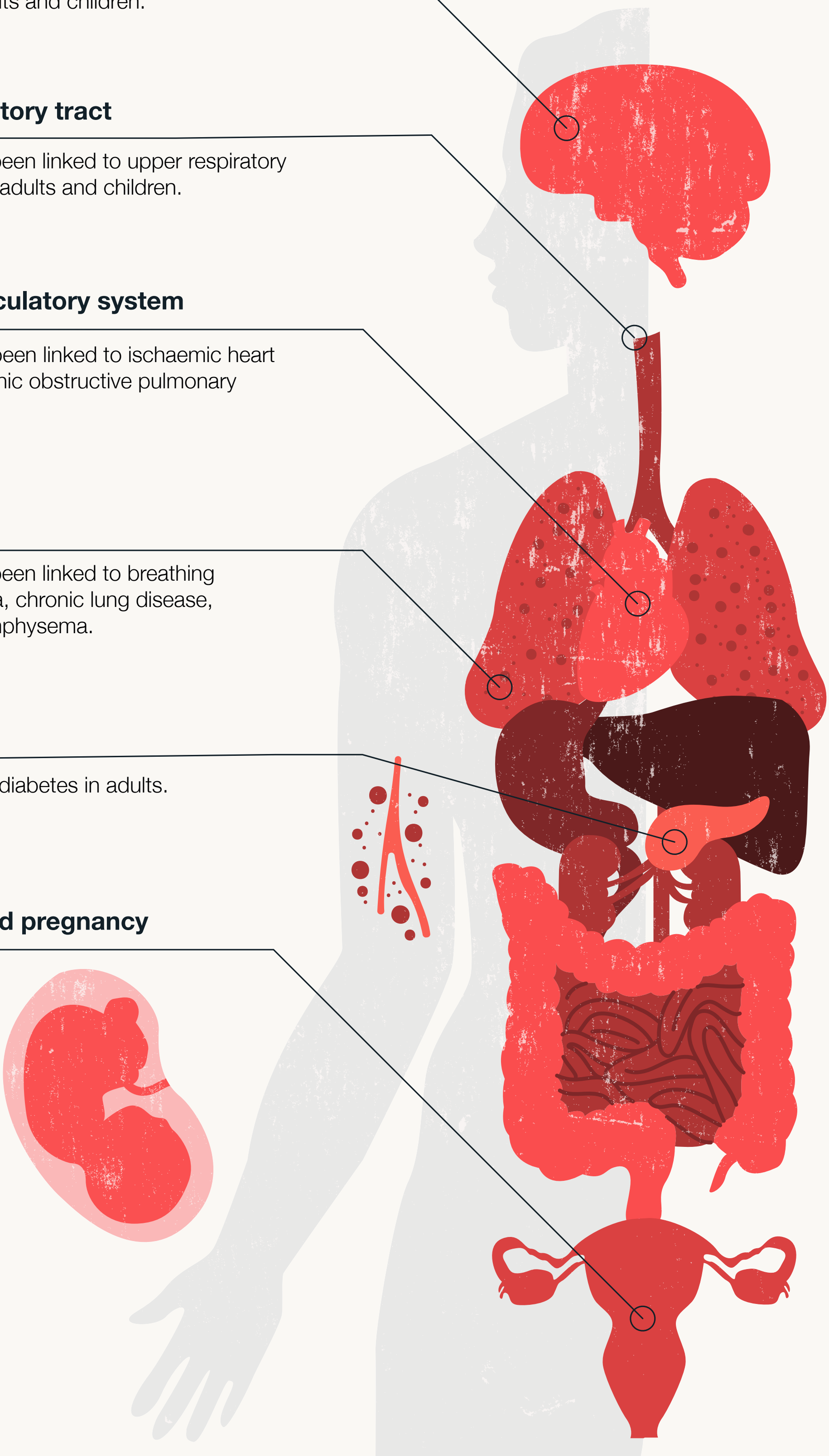
## 3.3.2 Asthma symptoms in children and young adults

$PM_{10}$ pollution is also known to trigger asthma attacks and symptoms for people with asthma. Children and young adults are at particularly high risk. We find that each year, there are 1,800 to 27,000 incidents where people in Australia aged 5-19 years experience asthma symptoms attributable to emissions from coal-burning power stations (Table 4). Some asthma symptoms are attributable to cross-state power station pollution. The power station groups in Melbourne and Sydney both contribute asthma symptoms in four other states (Tables A2.3 and A2.4).

| Person days with asthma symptoms (total cases per year) | | | |
|---|---|---|---|
| **Power station group** | **95%-confidence interval** | | |
| | **Best estimate** | **Low estimate** | **High estimate** |
| **Total** | **14,434** | **1,816** | **27,305** |
| Brisbane | 1,023 | 129 | 1,934 |
| Melbourne | 4,376 | 550 | 8,277 |
| Perth | 807 | 102 | 1,526 |
| Rockhampton | 647 | 81 | 1,222 |
| Sydney | 7,582 | 953 | 14,345 |

**Table 4.** Number of days and persons aged 5-19 where asthma symptoms are observed that are attributable to emissions from coal-burning power stations in Australia.

# Effects of air pollution on human health



**Brain**

Air pollution has been linked to fatigue, headache, anxiety, dementia, cognitive disorders, memory loss and ADHD in adults and children.

**Upper respiratory tract**

Air pollution has been linked to upper respiratory tract infections in adults and children.

**Heart and circulatory system**

Air pollution has been linked to ischaemic heart disease and chronic obstructive pulmonary disease in adults.

**Lungs**

Air pollution has been linked to breathing problems, asthma, chronic lung disease, bronchitis and emphysema.

**Pancreas**

Air pollution has been linked to diabetes in adults.

**Reproductive system and pregnancy**

Air pollution has been linked to infertility, pre-term birth and developmental disorders in the developing fetus.

### 3.3.3 Premature deaths

There are well established relationships between $PM_{2.5}$ and $NO_2$ pollution and premature death.  We find that the pollution from the power stations in Australia is responsible for approximately 800 additional premature deaths each year (95%-confidence interval: 373 to 1310). The results are shown per power station group in Table 5. Premature deaths occur in states located considerable distances away from the emitting power stations, for example premature deaths in Australian Capital Territory, New South Wales, South Australia and Tasmania are attributed to the Melbourne power station group in addition to those in Victoria (Table A3.5).

| Power station group | 95%-confidence interval | | |
|---|---|---|---|
| | Best estimate | Low estimate | High estimate |
| **Total** | **785** | **373** | **1,310** |
| Brisbane | 39 | 18 | 63 |
| Melbourne | 205 | 98 | 339 |
| Perth | 31 | 15 | 50 |
| Rockhampton | 34 | 16 | 57 |
| Sydney | 477 | 226 | 801 |

**Table 5:** Modelled number of annual premature deaths due to pollution from coal-burning power stations in Australia by power station group.

Hazelwood, operated by French utility Engie in the Latrobe Valley, was the dirtiest power station in the developed world until its closure.
© Jeremy Buckingham MLC

# 4.0 Discussion and recommendations

This report has highlighted the significant harmful health impacts of burning coal for electricity. It has documented how coal-burning power stations worsen air quality, impact the health of Australians and spread persistent environmental pollutants such as mercury across large areas of Australia. The coal power industry continues to profit from environmental degradation, avoidable illness and premature death.

The estimates of mortality presented here rely on conservative population data and only include a subset of real world pollutants and health impacts associated with coal power. For example we do not account for the health impacts of ozone pollution in the analysis. Regardless, the estimated mortality from coal power stations in Australia is comparable to the national road toll and outnumbers by far the number of deaths from most other publicly-debated safety risks, such as airplane accidents, shark attacks, lightning strikes, natural disasters, terrorist attacks and other homicides (Table 6 and Figure 13).

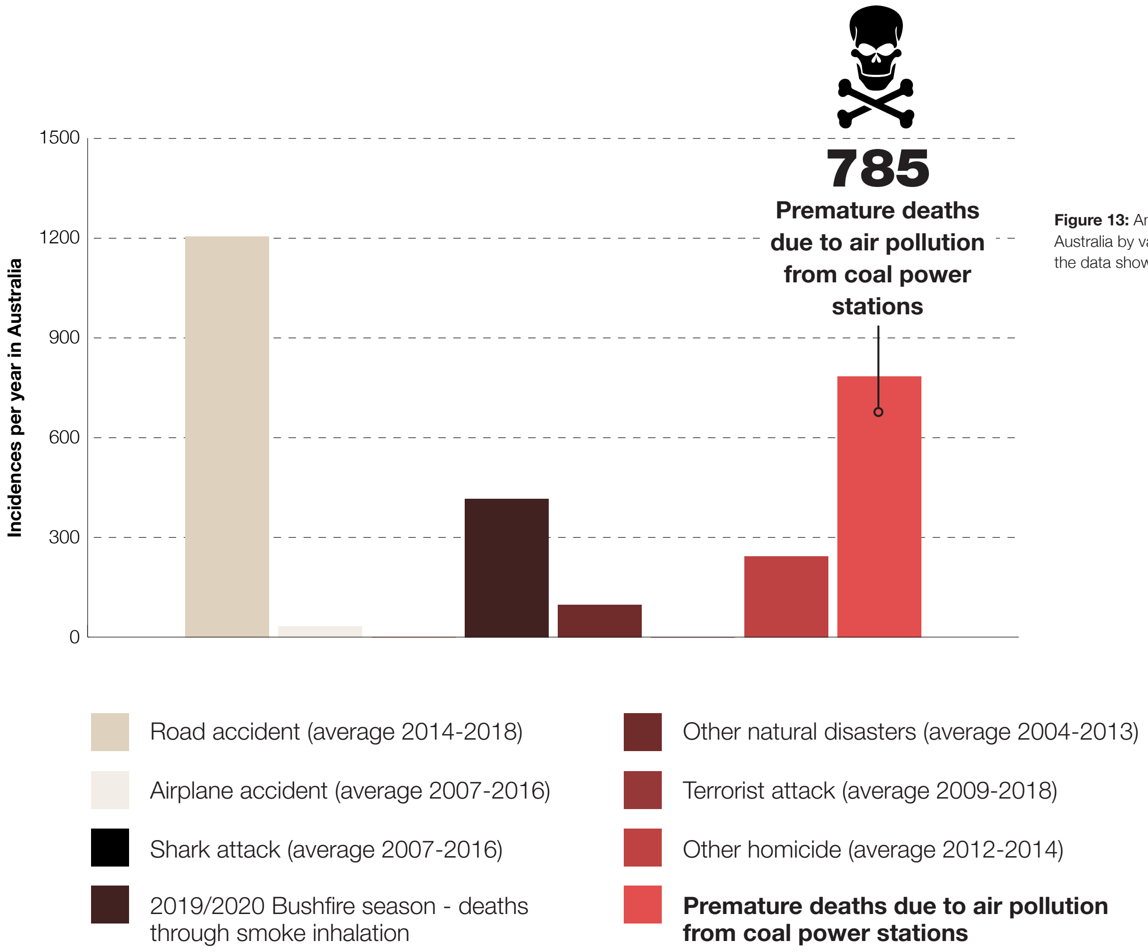
As other studies have shown, there is also strong evidence linking exposure to air pollution and increased risk of severe COVID-19 infections and mortality in the population.[68] By failing to address air pollution caused by poorly regulated coal-burning power stations we are unnecessarily compounding the population's susceptibility to COVID-19 and diseases like it.

**Table 6:** Annual premature deaths in Australia by various causes.

| Cause of death | Incidences per year in Australia |
|---|---|
| Road accident (average 2009-2018)[69] | 1,262 |
| Airplane accident (average 2007-2016)[70] | 34 |
| Shark attack (average 2007-2016)[71] | 2 |
| 2019/2020 Bushfire season - deaths through smoke inhalation[72] | 417 |
| Other natural disasters (average 2004-2013)[73] | 98 |
| Terrorist attack (average 2009-2018)[74] | 1 |
| Other homicide (average 2012-2014)[75] | 244 |
| **Premature death due to air pollution from coal power stations** | **785** |

Fortunately, clean renewable energy technologies like solar and wind are now the cheapest source of new supply in Australia.[76] There are no technological impediments to shifting Australia to 100% renewable energy within a decade, with enough policy support from the government.[77]

In the meantime, Australia's regulation of power station pollution is weak by global standards. While emission limits vary by jurisdiction, NSW power stations are allowed to emit around eight times more sulfur dioxide, seven and a half times more nitrogen dioxide, and up to five times more fine particle pollution than would be permitted under the European Emissions Directive.[78] Similar conclusions can be drawn for every other jurisdiction in Australia, all of which observe emission limits that are multiple times higher than in the United States, China, Germany or Japan.



**785**

**Premature deaths due to air pollution from coal power stations**

**Figure 13:** Annual premature deaths in Australia by various causes. (visualisation of the data shown in Table 6)

Mercury controls are similarly weak, with power stations allowed to emit 33 times more mercury than in the United States or China, with Australia being one of the only OECD countries not to have ratified the Minamata Convention to reduce global emissions of mercury.[79] Some power stations have no mercury emission limit in their licenses at all - for instance, the most mercury-intensive lignite power stations in Victoria have no mercury emission limit at all.

No Australian power station is currently required to fit best practice pollution control technologies, which would require Flue Gas Desulfurisation, Selective Catalytic Reduction, Activated Carbon Injection and bag filters, despite these measures being required in most power stations globally.

If Australia moves to renewable energy over the next decade, it is possible to mitigate the health impacts during that period. There is no reason why governments could not require this until the last coal-burning power station has been replaced with zero emissions energy.

Air pollution protest
© Greenpeace/Wason Wanichakorn

La Trobe Valley coal-burning power station air pollution
© Greenpeace

# Recommendations for policy-makers

Greenpeace Australia Pacific recommends the following measures to mitigate the health effects of pollution from coal-burning power stations.

- Develop a plan to ensure coal is completely phased out and replaced with renewable energy in the shortest possible time, with regional plans to prepare communities for economic adjustment.
- Significantly tighten emission limits in existing power stations equivalent to the lower atmospheric emission limit described by the European Industrial Emission Directive best available technique conclusions, until their closure.
- Ensure any load-based licensing or pollution fee schemes reflect the damage to human health and costs to the healthcare system caused by air pollution, to ensure these costs are no longer externalised by electricity generators.
- Conduct independent health-risk assessments for major sources of air pollution to ensure air pollution policy reflects the best available public health evidence.
- Adopt the advice of peak health organisations on the appropriate science-based values for ambient air quality standards for sulfur dioxide, nitrogen dioxide and ozone.
- Ratify and implement the Minamata convention, the International treaty on mercury emission reduction.

# Glossary

| | |
|---|---|
| **Air pollutant** | An unwanted substance found in the air in the form of a solid particle, a liquid droplet or a gas. The substance may be hazardous, harmful to human health if inhaled or damaging to the environment. Prominent examples are $PM_{2.5}$, The nox group and $SO_2$.<br>Synonym (here): pollutant |
| **Air quality guideline** | A guideline for the pollutant concentration, issued by the who. Pollutant concentrations above the guideline value are shown to be harmful to human health. According to the who, there is no safe level of particulate pollution, meaning any reduction in pollution will result in public health benefits. Harmful impacts for gaseous pollutants have been shown on pollution levels below these guidelines. |
| **Best estimate** | See confidence interval |
| **Bituminous coal** | A medium grade coal, containing bitumen. It has a relatively high carbon content (~60-80%) and gross calorific value compared with lower grade coals. |
| **Capacity** | The maximum electrical power that a power station can generate. |
| **Confidence interval** | Our health assessment model uses empirical data such as population numbers, background death rates and others. The true values of these variables are not known with infinite precision: no model study can give results with absolute certainty. Instead, we provide a range (interval), which most likely contains the true value. In this work, we use the 95% confidence interval. That means that with 95% probability, reality is somewhere inside the confidence interval and with 5% chance it is actually outside this interval (above or below). The value which has the highest probability to be the true value is called the best estimate. It is somewhere inside the confidence interval. The bounds of the confidence interval are called low and high estimate<br>Synonyms: 95%-confidence interval (in this work), “between x and y” |
| **Emission limit** | The maximum allowed emission concentration (or sometimes emission rate) for a specific station. It can be prescribed by national standards, environmental permit conditions (which can be based on the national standard but can also be looser or stricter) or some other legal regulation. |
| **Emission rate** | The amount of a pollutant that is emitted per unit of time by a specific power station (e.g. 100 Kg/hour). In some cases, this is used instead of the emission concentration as a measure of how polluting the coal-burning power station is. |
| **Exceedance** | A period of time when the concentration of an air pollutant is greater than the appropriate air quality guideline. Not to be confused with: excess pollution |
| **Excess pollution** | (Only used in the appendix) air pollution and mercury deposition originating from coal-burning power stations (excess to the pollution level that would be there in the absence of the power stations). Not to be confused with: exceedance |
| **Fine particle(s)** | $PM_{2.5}$ |
| **Flue gas** | The gas that exits the power station via its stacks. |
| **High estimate** | See confidence interval |
| **Lignite** | A low grade coal, sometimes known as brown coal. It has a relatively low carbon content (~25-35%) and low gross calorific value compared with higher grade coals. |
| **Low estimate** | See confidence interval |
| **Maximum 24-hour concentration** | The highest measured or modelled pollutant concentration, when averaging over 24-hour periods. This is not a regulation or a guideline, but an event that really occurs (or is modeled to occur). Correspondingly for other time periods (1 hour, 10 minutes).<br>Not to be confused with: air quality guideline, emission limit. |

| | |
|---|---|
| **MPa** | Megapascal (unit of pressure). The pressure of the atmosphere is 0.1 MPa. |
| **NO** | Nitrogen monoxide. A trace gas that is produced in all combustion processes. It converts from and to $NO_2$.<br>Synonym: Nitric Oxide |
| **$NO_2$** | Nitrogen Dioxide. A trace gas that is produced in all combustion processes. It converts from and to no. The amount of $no_2$ in the atmosphere is commonly used as a proxy to assess the health impact of the whole nox group. |
| **$NO_x$** | Nitrogen Oxides. A generic term for NO and $NO_2$, a group of trace gases that are harmful to human health. |
| **$PM_{2.5}$** | Fine particulate matter / fine particles. Solid particles with aerodynamic diameter of less than 2.5µm (i. E. Small dust particles). They are so small that they can pass from the lungs into the bloodstream, affecting the entire cardiovascular system and causing a range of health impacts. Due to their small size, the particles stay airborne for a long time and can travel hundreds or thousands of kilometres. Fossil fuel combustion emits $PM_{2.5}$ Directly, as fly ash and other unburned particles, and contributes to $PM_{2.5}$ Indirectly through emissions of gaseous pollutants (particularly $so_2$ and nox) which form $PM_{2.5}$ In the atmosphere. $PM_{2.5}$ Is harmful to human health and thus an air pollutant. |
| **Pollutant concentration** | The actual concentration of some pollutant at any location (close to or far away from a power station). This is the concentration that the local population is exposed to, which means that the impact on public health is determined by this value. The pollutant concentration can be above and the air quality guideline (i. E. Violating it) or below (i. E. Complying with it). |
| **$SO_2$** | Sulfur dioxide. Sulfur dioxide is a trace gas produced by industrial processing of materials that contain sulfur, including burning coal in power stations and processing of some mineral ores. Human sources of $so_2$ far exceed all natural sources even when accounting for volcanic activity. Sulfur dioxide reacts with other substances to form harmful compounds, such as sulfuric acid ($H_2SO_4$), sulfurous acid ($H_2SO_3$) and sulfate particles and it is therefore a cause of acid rain and particulate matter pollution. |
| **Subbituminous coal** | An intermediate grade coal, sometimes known as black lignite. Its carbon content of (~40-50%) and gross calorific value are between those of lignite and bituminous coal. |
| **Subcritical** | Conventional coal-burning power stations operate at boiler conditions that are physically described as subcritical. The water used by the generator to drive the turbine is boiled to generate steam which drives the turbines. The turbine water is not elevated to supercritical temperature and pressure. Subcritical coal-burning power stations have a thermal efficiency of <35%<br>Note: in this context, the term critical does not indicate a “crisis” or an “out-of-control point”, as it does in every-day language. |
| **Supercritical** | When operating at supercritical conditions, the boiler water is at temperature and pressure so high that it assumes an exotic physical state: it is no longer distinguishable whether it is a gas or a liquid. Supercritical coal-burning power stations achieve higher thermal efficiency by operating at pressures of 22-25 MPa and temperatures of 540-580°c. Supercritical coal-burning power stations have a thermal efficiency of 35-40%. |
| **Thermal efficiency** | (By far) not all physical energy that is released in the combustion process can be converted to electric energy. Thermal efficiency describes the fraction of the energy available in the fuel consumed that is converted to saleable electricity. |
| **WHO** | World Health Organisation |
| **µg** | Microgram. A millionth of a gram. |

# Appendix

## A.1. Power station geometry and emission data

The pollutant emission rates and flue gas release characteristics used for the modeling are based, as far as possible, on self-reported data by power station owners and government sources. Where necessary this was supplemented with other publicly available information. Data was collected from the following sources:

- Reported annual emissions to the National Pollutant Inventory[80,81]
- Generation dispatch reports and hours of operation/year from AEMO dispatch reports National Electricity Market[82] and South-West Interconnected System[83]
- Unit age, capacity and thermal efficiency[84]
- Calorific value of coal[85]
- Flue gas volume flow (FGV)[86]
- Flue gas exit speed and temperature[87,88,89]
- Stack height
- Stack location

The stack inner diameter was measured from high-resolution satellite imagery, when actual information was not available from regulatory sources or literature. The power station and emission data shown in Tables A1 and A2 are used as the basis of modelling the stations' air quality impacts using the CALMET-CALPUFF modeling system.

**Table A1.1** Stack and flue gas characteristics of the modelled power stations.

| Station | Unit | Power station group | Stack | | | | Flue gas | |
|---|---|---|---|---|---|---|---|---|
| | | | Latitude | Longitude | Height | Diameter | Exit speed | Temperature |
| | | | (deg) | (deg) | (m) | (m) | (m/s) | (°C) |
| Kogan Creek | 1 | Brisbane | -26.9177 | 150.7493 | 160 | 6.2 | 12.8 | 129.9 |
| Millmerran | 1 | Brisbane | -27.9615 | 151.2789 | 141 | 7.1 | 11.2 | 129.9 |
| Millmerran | 2 | Brisbane | -27.9615 | 151.2789 | 141 | 7.1 | 11.2 | 129.9 |
| Tarong | 1 | Brisbane | -26.7824 | 151.9153 | 210 | 9.0 | 11.4 | 129.9 |
| Tarong | 2 | Brisbane | -26.7824 | 151.9153 | 210 | 9.0 | 11.4 | 129.9 |
| Tarong | 3 | Brisbane | -26.7824 | 151.9153 | 210 | 9.0 | 11.4 | 129.9 |
| Tarong | 4 | Brisbane | -26.7824 | 151.9153 | 210 | 9.0 | 11.4 | 129.9 |
| Tarong North | 1 | Brisbane | -26.7758 | 151.9146 | 210 | 6.4 | 7.3 | 129.9 |
| Loy Yang B | 1 | Melbourne | -38.2564 | 146.5864 | 255 | 9.0 | 11.2 | 187.0 |
| Loy Yang B | 2 | Melbourne | -38.2564 | 146.5864 | 255 | 9.0 | 11.2 | 187.0 |
| Loy Yang A | 1 | Melbourne | -38.2536 | 146.5746 | 260 | 9.0 | 11.9 | 129.9 |
| Loy Yang A | 2 | Melbourne | -38.2536 | 146.5746 | 260 | 9.0 | 11.9 | 129.9 |
| Loy Yang A | 3 | Melbourne | -38.2536 | 146.5746 | 260 | 9.0 | 12.6 | 129.9 |
| Loy Yang A | 4 | Melbourne | -38.2536 | 146.5746 | 260 | 9.0 | 12.6 | 129.9 |
| Yallourn Power Station | 1 | Melbourne | -38.1770 | 146.3428 | 168 | 10.0 | 6.4 | 129.9 |
| Yallourn Power Station | 2 | Melbourne | -38.1770 | 146.3428 | 168 | 10.0 | 6.4 | 129.9 |
| Yallourn Power Station | 3 | Melbourne | -38.1770 | 146.3428 | 168 | 8.4 | 9.7 | 129.9 |

| Station | Unit | Power station group | Stack | | | | Flue gas | |
|---|---|---|---|---|---|---|---|---|
| | | | Latitude | Longitude | Height | Diameter | Exit speed | Temperature |
| | | | (deg) | (deg) | (m) | (m) | (m/s) | (°C) |
| Yallourn Power Station | 4 | Melbourne | -38.1770 | 146.3428 | 168 | 8.4 | 9.7 | 129.9 |
| Bluewaters | 2 | Perth | -33.3322 | 116.2280 | 100 | 4.1 | 8.4 | 129.9 |
| Bluewaters 2 | 1 | Perth | -33.3322 | 116.2280 | 100 | 4.1 | 8.4 | 129.9 |
| Collie | 1 | Perth | -33.3431 | 116.2608 | 170 | 5.2 | 7.7 | 152.0 |
| Muja-C | 5 | Perth | -33.4456 | 116.3075 | 151 | 5.9 | 20.4 | 133.0 |
| Muja-C | 6 | Perth | -33.4456 | 116.3075 | 151 | 5.9 | 20.4 | 133.0 |
| Muja-D | 7 | Perth | -33.4456 | 116.3075 | 151 | 5.9 | 19.0 | 133.0 |
| Muja-D | 8 | Perth | -33.4456 | 116.3075 | 151 | 5.9 | 19.0 | 133.0 |
| Worsley Alumina | 1 | Perth | -33.2352 | 116.0687 | 76 | 2.3 | 26.0 | 130.0 |
| Worsley Alumina | 2 | Perth | -33.2352 | 116.0687 | 76 | 2.3 | 22.0 | 130.0 |
| Worsley Alumina | 3 | Perth | -33.2352 | 116.0687 | 76 | 2.3 | 25.5 | 130.0 |
| Worsley Alumina | 4 | Perth | -33.2352 | 116.0687 | 76 | 2.3 | 24.5 | 130.0 |
| Worsley Alumina | 5 | Perth | -33.2352 | 116.0687 | 76 | 2.3 | 24.5 | 130.0 |
| Callide B | 1 | Rockhampton | -24.3449 | 150.6197 | 210 | 7.0 | 9.4 | 129.9 |
| Callide B | 2 | Rockhampton | -24.3449 | 150.6197 | 210 | 7.0 | 9.4 | 129.9 |
| Callide C | 3 | Rockhampton | -24.3449 | 150.6197 | 230 | 6.4 | 13.2 | 135.0 |
| Callide C | 4 | Rockhampton | -24.3449 | 150.6197 | 230 | 6.4 | 13.2 | 135.0 |
| Gladstone | 1 | Rockhampton | -23.8508 | 151.2187 | 153 | 8.0 | 15.0 | 129.9 |
| Gladstone | 2 | Rockhampton | -23.8508 | 151.2187 | 153 | 8.0 | 15.0 | 129.9 |
| Gladstone | 3 | Rockhampton | -23.8508 | 151.2187 | 153 | 8.0 | 15.0 | 129.9 |
| Gladstone | 4 | Rockhampton | -23.8508 | 151.2187 | 153 | 8.0 | 15.0 | 129.9 |
| Gladstone | 5 | Rockhampton | -23.8508 | 151.2187 | 153 | 8.0 | 15.0 | 129.9 |
| Gladstone | 6 | Rockhampton | -23.8508 | 151.2187 | 153 | 8.0 | 15.0 | 129.9 |
| Stanwell | 1 | Rockhampton | -23.5097 | 150.3195 | 210 | 9.0 | 11.9 | 129.9 |
| Stanwell | 2 | Rockhampton | -23.5097 | 150.3195 | 210 | 9.0 | 11.9 | 129.9 |
| Stanwell | 3 | Rockhampton | -23.5097 | 150.3195 | 210 | 9.0 | 11.9 | 129.9 |
| Stanwell | 4 | Rockhampton | -23.5097 | 150.3195 | 210 | 9.0 | 11.9 | 129.9 |
| Bayswater | 1 | Sydney | -32.3953 | 150.9491 | 250 | 10.6 | 15.6 | 129.9 |
| Bayswater | 2 | Sydney | -32.3953 | 150.9491 | 250 | 10.6 | 15.6 | 129.9 |
| Bayswater | 3 | Sydney | -32.3953 | 150.9491 | 250 | 10.6 | 15.6 | 129.9 |
| Bayswater | 4 | Sydney | -32.3953 | 150.9491 | 250 | 10.6 | 15.6 | 129.9 |
| Eraring | 1 | Sydney | -33.0617 | 151.5223 | 200 | 10.5 | 17.8 | 127.0 |
| Eraring | 2 | Sydney | -33.0617 | 151.5223 | 200 | 10.5 | 17.8 | 122.0 |

| Station | Unit | Power station group | Stack | | | | Flue gas | |
|---|---|---|---|---|---|---|---|---|
| | | | Latitude | Longitude | Height | Diameter | Exit speed | Temperature |
| | | | (deg) | (deg) | (m) | (m) | (m/s) | (°C) |
| Eraring | 3 | Sydney | -33.0617 | 151.5223 | 200 | 10.5 | 17.8 | 122.0 |
| Eraring | 4 | Sydney | -33.0617 | 151.5223 | 200 | 10.5 | 17.8 | 121.0 |
| Liddell | 1 | Sydney | -32.3700 | 150.9800 | 168 | 8.7 | 17.5 | 129.9 |
| Liddell | 2 | Sydney | -32.3700 | 150.9800 | 168 | 8.7 | 17.5 | 129.9 |
| Liddell | 3 | Sydney | -32.3700 | 150.9800 | 168 | 8.7 | 17.5 | 129.9 |
| Liddell | 4 | Sydney | -32.3700 | 150.9800 | 168 | 8.7 | 17.5 | 129.9 |
| Mt Piper | 1 | Sydney | -33.3589 | 150.0313 | 250 | 11.0 | 7.1 | 129.0 |
| Mt Piper | 2 | Sydney | -33.3589 | 150.0313 | 250 | 11.0 | 7.1 | 115.0 |
| Vales Point B | 5 | Sydney | -33.1607 | 151.5431 | 178 | 10.3 | 4.9 | 95.5 |
| Vales Point B | 6 | Sydney | -33.1607 | 151.5431 | 178 | 10.3 | 4.9 | 112.5 |

**Table A1.2.** Modelled baseline emission rates (metric units[90]).

| Station | Unit | power station group | Emissions | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mercury | $NO_x$ | $SO_2$ | $PM_{10}$ | $PM_{2.5}$ |
| | | | (kg/a) | (kt/a) | (kt/a) | (t/a) | (t/a) |
| Kogan Creek | 1 | Brisbane | 18.71 | 5.51 | 13.40 | 144 | 33 |
| Millmerran | 1 | Brisbane | 40.29 | 4.69 | 15.57 | 70 | 10 |
| Millmerran | 2 | Brisbane | 40.29 | 4.69 | 15.57 | 70 | 10 |
| Tarong | 1 | Brisbane | 13.48 | 5.23 | 1.18 | 1194 | 513 |
| Tarong | 2 | Brisbane | 13.48 | 5.23 | 1.18 | 1194 | 513 |
| Tarong | 3 | Brisbane | 13.48 | 5.23 | 1.18 | 1194 | 513 |
| Tarong | 4 | Brisbane | 13.48 | 5.23 | 1.18 | 1194 | 513 |
| Tarong North | 1 | Brisbane | 23.90 | 3.25 | 20.20 | 86 | 49 |
| Loy Yang B | 1 | Melbourne | 140.00 | 7.37 | 14.19 | 254 | 172 |
| Loy Yang B | 2 | Melbourne | 140.00 | 7.37 | 14.19 | 254 | 172 |
| Loy Yang A | 1 | Melbourne | 73.05 | 11.99 | 15.17 | 1217 | 191 |
| Loy Yang A | 2 | Melbourne | 73.05 | 11.99 | 15.17 | 1217 | 191 |
| Loy Yang A | 3 | Melbourne | 73.05 | 11.99 | 15.17 | 1217 | 191 |
| Loy Yang A | 4 | Melbourne | 73.05 | 11.99 | 15.17 | 1217 | 191 |
| Yallourn Power Station | 1 | Melbourne | 109.03 | 3.61 | 4.56 | 491 | 189 |
| Yallourn Power Station | 2 | Melbourne | 109.03 | 3.61 | 4.56 | 491 | 189 |
| Yallourn Power Station | 3 | Melbourne | 109.03 | 3.61 | 4.56 | 491 | 189 |
| Yallourn Power Station | 4 | Melbourne | 109.03 | 3.61 | 4.56 | 491 | 189 |
| Bluewaters | 2 | Perth | 7.97 | 1.64 | 6.63 | 28 | 13 |
| Bluewaters 2 | 1 | Perth | 7.97 | 1.64 | 6.63 | 28 | 13 |

| Station | Unit | power station group | Emissions | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mercury | NO$_x$ | SO$_2$ | PM$_{10}$ | PM$_{2.5}$ |
| | | | (kg/a) | (kt/a) | (kt/a) | (t/a) | (t/a) |
| Collie | 1 | Perth | 30.54 | 3.39 | 13.01 | 389 | 202 |
| Muja-C | 5 | Perth | 16.57 | 1.64 | 6.59 | 198 | 60 |
| Muja-C | 6 | Perth | 16.57 | 1.64 | 6.59 | 198 | 60 |
| Muja-D | 7 | Perth | 16.57 | 1.64 | 6.59 | 198 | 60 |
| Muja-D | 8 | Perth | 16.57 | 1.64 | 6.59 | 198 | 60 |
| Worsley Alumina | 1 | Perth | 1.72 | 0.91 | 2.49 | N/A[91] | N/A |
| Worsley Alumina | 2 | Perth | 1.72 | 0.90 | 2.78 | N/A | N/A |
| Worsley Alumina | 3 | Perth | 1.72 | 0.94 | 2.75 | N/A | N/A |
| Worsley Alumina | 4 | Perth | 2.89 | 1.56 | 2.74 | 16.81 | 8.79 |
| Worsley Alumina | 5 | Perth | 2.89 | 1.56 | 2.74 | 16.81<br>0 | 8.790 |
| Callide B | 1 | Rockhampton | 60.51 | 10.46 | 6.35 | 480 | 162 |
| Callide B | 2 | Rockhampton | 60.51 | 10.46 | 6.35 | 480 | 162 |
| Callide C | 3 | Rockhampton | 60.00 | 3.16 | 6.10 | 502 | 145 |
| Callide C | 4 | Rockhampton | 60.00 | 3.16 | 6.10 | 960 | 145 |
| Gladstone | 1 | Rockhampton | 18.50 | 6.85 | 5.23 | 25 | 9 |
| Gladstone | 2 | Rockhampton | 18.50 | 6.85 | 5.23 | 25 | 9 |
| Gladstone | 3 | Rockhampton | 18.50 | 6.85 | 5.23 | 25 | 9 |
| Gladstone | 4 | Rockhampton | 18.50 | 6.85 | 5.23 | 25 | 9 |
| Gladstone | 5 | Rockhampton | 18.50 | 6.85 | 5.23 | 25 | 9 |
| Gladstone | 6 | Rockhampton | 18.50 | 6.85 | 5.23 | 25 | 9 |
| Stanwell | 1 | Rockhampton | 23.87 | 9.08 | 9.28 | 188 | 93 |
| Stanwell | 2 | Rockhampton | 23.87 | 9.08 | 9.28 | 188 | 93 |
| Stanwell | 3 | Rockhampton | 23.87 | 9.08 | 9.28 | 188 | 93 |
| Stanwell | 4 | Rockhampton | 23.87 | 9.08 | 9.28 | 188 | 93 |
| Bayswater | 1 | Sydney | 16.38 | 8.14 | 11.03 | 251 | 90 |
| Bayswater | 2 | Sydney | 16.38 | 8.14 | 11.03 | 251 | 90 |
| Bayswater | 3 | Sydney | 16.38 | 8.14 | 11.03 | 251 | 90 |
| Bayswater | 4 | Sydney | 16.38 | 8.14 | 11.03 | 251 | 90 |
| Eraring | 1 | Sydney | 3.71 | 5.35 | 9.83 | 83 | 33 |
| Eraring | 2 | Sydney | 3.71 | 5.35 | 9.83 | 83 | 33 |
| Eraring | 3 | Sydney | 3.71 | 5.35 | 9.83 | 83 | 33 |
| Eraring | 4 | Sydney | 3.71 | 5.35 | 9.83 | 83 | 33 |

| Station | Unit | power station group | Emissions | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mercury | $NO_x$ | $SO_2$ | $PM_{10}$ | $PM_{2.5}$ |
| | | | (kg/a) | (kt/a) | (kt/a) | (t/a) | (t/a) |
| Liddell | 1 | Sydney | 8.49 | 4.28 | 7.12 | 129 | 55 |
| Liddell | 2 | Sydney | 8.49 | 4.28 | 7.12 | 129 | 55 |
| Liddell | 3 | Sydney | 8.49 | 4.28 | 7.12 | 129 | 55 |
| Liddell | 4 | Sydney | 8.49 | 4.28 | 7.12 | 129 | 55 |
| Mt Piper | 1 | Sydney | 14.52 | 10.51 | 15.00 | 77 | 28 |
| Mt Piper | 2 | Sydney | 14.52 | 10.51 | 15.00 | 77 | 28 |
| Vales Point B | 5 | Sydney | 1.26 | 10.23 | 10.32 | 58 | 23 |
| Vales Point B | 6 | Sydney | 1.26 | 10.23 | 10.32 | 58 | 23 |

**Figure A1.2.** Electricity output (MW) versus time for each of the modelled units in 2018.

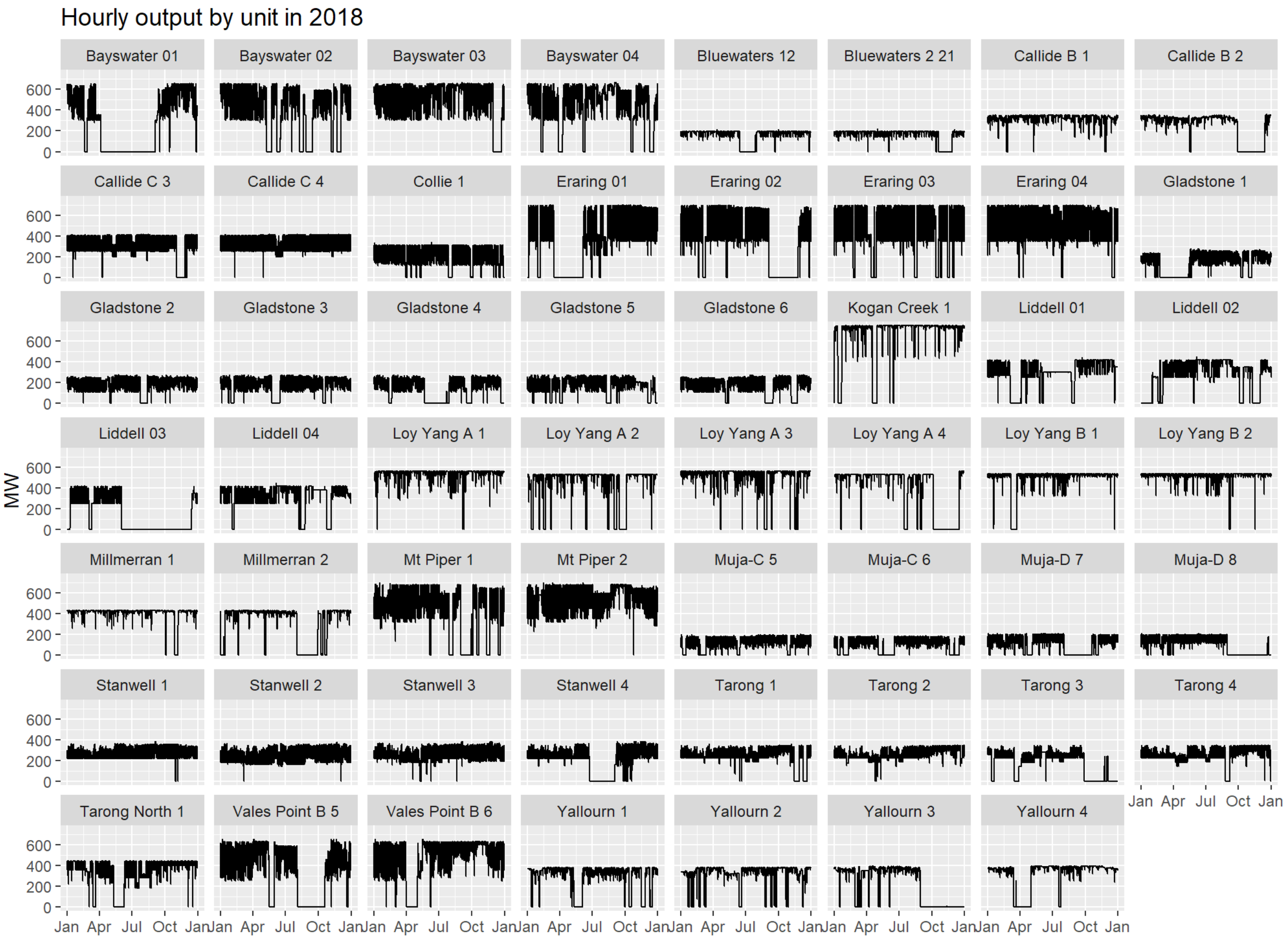


**Table A1.3.** Load relative to full capacity averaged over the full year 2018 (capacity-weighted mean over all units of each power station).

| Station | Power station group | Average load (%) |
|---|---|---|
| Kogan Creek | Brisbane | 90.9 |
| Millmerran | Brisbane | 84.3 |
| Tarong | Brisbane | 65.4 |
| Tarong North | Brisbane | 77.9 |
| Loy Yang A | Melbourne | 85.6 |
| Loy Yang B | Melbourne | 93.5 |
| Yallourn Power Station | Melbourne | 73.5 |
| Bluewaters | Perth | 76.4 |
| Bluewaters 2 | Perth | 76.4 |
| Collie | Perth | 58.6 |
| Muja-C | Perth | 52.6 |
| Muja-D | Perth | 46.9 |
| Callide B | Rockhampton | 78.6 |
| Callide C | Rockhampton | 87.6 |
| Gladstone | Rockhampton | 61.5 |
| Stanwell | Rockhampton | 63.5 |
| Bayswater | Sydney | 63.1 |
| Eraring | Sydney | 69.9 |
| Liddell | Sydney | 58.1 |
| Mt Piper | Sydney | 71.1 |
| Vales Point B | Sydney | 65.5 |

# A.2 Human Health Impacts Supplementary Tables

**Table A2.1:** Modelled number of annual cases of low birth weight due to cross state $PM_{2.5}$ pollution from coal-burning power stations in Australia; ratio: fraction of the total cases attributed to the power station group.

| Low birth weight due to cross-state pollution (cases per year) | | | | |
|---|---|---|---|---|
| **Power station group** | **95%-confidence interval** | | | **Ratio (%)** |
| | **Best estimate** | **Low estimate** | **High estimate** | |
| **Total** | **51** | **27** | **75** | **6.1** |
| Brisbane | 12 | 7 | 18 | 22.2 |
| Melbourne | 21 | 11 | 30 | 7.9 |
| Perth | 0 | 0 | 0 | 0.0 |
| Rockhampton | 1 | 1 | 2 | 4.0 |
| Sydney | 17 | 9 | 25 | 3.8 |

**Table A2.2:** Modelled number of annual cases of low birth weight due to $PM_{2.5}$ pollution from coal-burning power stations in Australia - per emitting power station group and residence state or territory of the victim.

| **Power station group** | **Residence of victim** | **95%-confidence interval** | | |
|---|---|---|---|---|
| | | **best estimate** | **low estimate** | **high estimate** |
| **Total** | | **845** | **439** | **1,253** |
| Brisbane | New South Wales | 12 | 7 | 18 |
| Brisbane | Queensland | 43 | 23 | 63 |
| Melbourne | Australian Capital Territory | 1 | 0 | 1 |
| Melbourne | New South Wales | 16 | 8 | 23 |
| Melbourne | South Australia | 1 | 1 | 2 |
| Melbourne | Tasmania | 3 | 1 | 4 |
| Melbourne | Victoria | 238 | 124 | 353 |
| Perth | Western Australia | 47 | 24 | 68 |
| Rockhampton | New South Wales | 1 | 1 | 2 |
| Rockhampton | Queensland | 34 | 18 | 49 |
| Sydney | Australian Capital Territory | 3 | 2 | 4 |
| Sydney | New South Wales | 433 | 224 | 644 |
| Sydney | Queensland | 5 | 2 | 7 |
| Sydney | Victoria | 10 | 5 | 14 |

**Table A2.3.** Number of days and persons aged 5-19 where asthma symptoms are observed that are attributable to cross-state pollution from coal-burning power stations in Australia. Ratio: fraction of the total cases attributed to the power station group

| Person days with asthma symptoms due to cross-state pollution (cases per year) | | | | |
|---|---|---|---|---|
| Power station group | 95%-confidence interval | | | Ratio (%) |
| | Best estimate | Low estimate | High estimate | |
| **Total** | **894** | **113** | **1,689** | **6.2** |
| Brisbane | 218 | 28 | 413 | 21.4 |
| Melbourne | 352 | 44 | 665 | 8.0 |
| Perth | 0 | 0 | 0 | 0.0 |
| Rockhampton | 24 | 3 | 45 | 3.7 |
| Sydney | 300 | 38 | 566 | 4.0 |

**Table A2.4:** Modelled annual number of days and persons aged 5-19 where asthma symptoms are observed due to PM$_{10}$ pollution from coal-burning power stations in Australia - per emitting power station group and residence state or territory of the victim.

| Power station group | Residence of victim | 95%-confidence interval | | |
|---|---|---|---|---|
| | | best estimate | low estimate | high estimate |
| **Total** | | **14,434** | **1,816** | **27,305** |
| Brisbane | New South Wales | 218 | 28 | 413 |
| Brisbane | Queensland | 805 | 101 | 1,521 |
| Melbourne | Australian Capital Territory | 13 | 2 | 25 |
| Melbourne | New South Wales | 272 | 34 | 514 |
| Melbourne | South Australia | 23 | 3 | 43 |
| Melbourne | Tasmania | 44 | 6 | 84 |
| Melbourne | Victoria | 4,024 | 506 | 7,612 |
| Perth | Western Australia | 807 | 102 | 1,526 |
| Rockhampton | New South Wales | 24 | 3 | 45 |
| Rockhampton | Queensland | 623 | 78 | 1,177 |
| Sydney | Australian Capital Territory | 50 | 6 | 95 |
| Sydney | Jervis Bay Territory | 0 | 0 | 1 |
| Sydney | New South Wales | 7,282 | 916 | 13,779 |
| Sydney | Queensland | 85 | 11 | 161 |
| Sydney | Victoria | 164 | 21 | 310 |

**Table A2.5:** Modelled number of annual premature deaths due to pollution from coal-burning power stations in Australia by power station group and residence state or territory of the victim.

| Power station group | Residence of victim | 95%-confidence interval | | |
|---|---|---|---|---|
| | | best estimate | low estimate | high estimate |
| **Total** | | **785** | **373** | **1,310** |
| Brisbane | New South Wales | 7 | 3 | 11 |
| Brisbane | Queensland | 32 | 15 | 52 |
| Melbourne | Australian Capital Territory | 1 | 0 | 1 |
| Melbourne | New South Wales | 11 | 5 | 19 |
| Melbourne | South Australia | 1 | 0 | 1 |
| Melbourne | Tasmania | 2 | 1 | 3 |
| Melbourne | Victoria | 190 | 91 | 314 |
| Perth | Western Australia | 31 | 15 | 50 |
| Rockhampton | New South Wales | 1 | 0 | 1 |
| Rockhampton | Queensland | 34 | 16 | 56 |
| Sydney | Australian Capital Territory | 2 | 1 | 3 |
| Sydney | New South Wales | 466 | 220 | 782 |
| Sydney | Queensland | 3 | 2 | 6 |
| Sydney | Victoria | 6 | 3 | 9 |

# Endnotes

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47 The World Bank. (2019). World Development Indicators. Retrieved from https://databank.worldbank.org/source/world-development-indicators on 2020-08-11 by selecting: Database *World Development Indicators, Country Australia, Series Low-birthweight babies (% of births).*

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53 The word "may" ["...or may not", our interpretation] seems to suggest that 0% overlap is as likely as 33%.

54 Namely:

- That the low estimate is the conservative estimate (with respect to the null-hypothesis that air pollution causes no harm to human health at all).
- That the best estimate is the value that an impartial analyst considers most likely based on the available evidence, avoiding tendentious assumptions into either direction.
- That the high estimate represents what must be considered possible if the worst reasonably possible assumptions turn out to be true.

55 These are the values for concentrations below 20 $\mu g/m^3$, which is the case in Australia. In the source, the values are given for an increase of 5 $\mu g/m^3$, we converted them to 10 $\mu g/m^3$ increase.

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[90] Kg: kilograms, t: (metric) tons, kt: (metric) kilotons, a: year.

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No data could be found for particle emissions from units 1, 2 and 3 and these were excluded from the analysis. As a result, the health impacts from the Western Australian coal-burning power stations are considered to be slightly conservative.

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