The health burden of fine particle pollution from electricity generation in NSW

Dr Ben Ewald B.Med, PhD

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About the author

Dr Ben Ewald is a GP in Newcastle and a Senior Lecturer at University of Newcastle School of Medicine and Public Health.

He teaches in the epidemiology Masters program at the Centre for Clinical Epidemiology and Biostatistics at the University of Newcastle and coordinates the communicable disease epidemiology and research protocol design subjects as well as teaching in the undergraduate medical course.

He has a role in public health advocacy on issues of physical activity and health, and interpreting scholarship on environmental risks to health.

Current research directions include developing the use of aerobic training in the treatment of chronic disease in the general practice setting.

The author would like to acknowledge useful comments on a draft of this work by air pollution researchers Dr Geoff Morgan and Dr Andrew Gray.

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Executive summary

This report estimates the health burden of air pollution from individual coal-fired power stations in NSW. It is significant new research made possible by recent studies of particle characterisation and atmospheric transport of pollution.

The effects of air pollution on human health have been studied and known about for many decades, and the list of health problems to which air pollution contributes continues to grow in tandem with research. This list now includes heart disease, stroke, asthma attacks, low birth weight of babies, lung cancer and type 2 diabetes. Research has also demonstrated that reducing air pollution, even if exposure levels are already low, leads to better health.

The form of pollution that has the strongest effect on health is fine particles ($PM_{2.5}$) and one of the major sources of $PM_{2.5}$ in the Sydney Greater Metropolitan region is burning coal for electricity.

There are five coal-fired power stations in NSW – Bayswater and Liddell in the Upper Hunter Valley, Eraring and Vales Point on the Central Coast, and Mount Piper near Lithgow. This study examines the health burden from premature death, the incidence of low birth weight for babies, and new cases of type 2 diabetes that are attributable to $PM_{2.5}$ air pollution exposure from these power stations. Air pollution from the five NSW power stations is estimated to lead to 279 deaths or 2,614 'Years of Life Lost' every year for people aged 30 to 99. Each year, this pollution also causes 233 babies to be born weighing less than 2,500 g and causes 361 people who would not otherwise develop type 2 diabetes to develop this disease.

Table 1: Number of adverse health outcomes attributable to air pollution in the five NSW regions used for analysis.

	Sydney	Central Coast	Lower Hunter	Upper Hunter	Remainder	**Total**
Mortality	153	25	51	7	43	**279**
Years of life lost	1433	234	477	65	402	**2614**
Low birth weight	147	16	37	6	27	**233**
Incident diabetes	199	33	63	8	58	**361**

Eraring and Vales Point on the NSW Central Coast make the largest contribution to the health burden from power generation, since prevailing weather patterns are most likely to carry pollutants from these sources into the Sydney basin where the largest population resides.

Based on the current expected closure date of the NSW power stations, it is estimated that 3,429 additional deaths will occur in NSW between the present day and the closure of the last station.

Table 2: Adverse health outcomes attributable to power stations during their remaining years of operation.

Power station	Planned closure year	Remaining operation (years)	Number of expected deaths	Number of low birth weight babies	Number of new onset diabetes
Bayswater	2035	17	685	571	857
Liddell	2022	4	107	89	134
Eraring	2032	14	1,219	1,058	1,579
Vales Point	2030	12	547	475	709
Mount Piper	2042	24	871	835	1,133
Total			**3,429**	**3,029**	**4,412**

Note: This table includes only Sydney, Central Coast and Hunter regions.

It should be noted that this analysis only focuses on three health outcomes, and only on $PM_{2.5}$ pollution (including secondary particles generated from sulfur dioxide (SO_2) and oxides of nitrogen (NOx) pollution), so the full health impacts of power station pollution are even higher than stated here.

Australia has benefitted from the introduction of vehicle emissions standards brought in during the 1970s which have been progressively tightened to the current standards based on Euro 5. We would not allow the cars manufactured in the 1970s to be sold today. Fortunately, most of them are now off the road.

The coal-fired power stations built in the 1970s to 1990s, on the other hand, are still operating. Two of the five power stations have been required to upgrade from electrostatic precipitators to bag filters to catch primary particles, while the other three had this as original equipment. None of the power stations uses post-combustion capture of SO_2, which is the main driver of secondary fine particles that lead to air pollution-related health problems.

The continued operation of all the coal-fired generators in NSW imposes a substantial health burden that could be alleviated by imposing stricter licensing conditions for operation that would require post-combustion capture of SO_2 and NOx, or by bringing forward closure of plants where this is uneconomic.

The objective of this report is to estimate the health impact of emissions from current electricity generation so that the community better understands what they are being exposed to, and so that decision makers can include health implications of sources of generation in planning for future electricity supply.

Recommendations

1. Power stations should be required to install modern pollution control technology that greatly reduces emissions of SO_2 and NOx.
2. The licences for Australian coal-fired power stations should be amended to set stack emission limits consistent with international best practice.
3. Australia's coal-fired power stations should be required to conduct continuous stack monitoring for SO_2, NOx, particles and mercury, and this data should be made public in real time and as searchable retrospective data.
4. Further research should be commissioned to clarify areas of remaining uncertainty. This would include using detailed atmospheric dispersion modelling to estimate spatial variability of ground level air pollution across the populated areas of NSW, and extension of health analysis to include lung cancer and non-fatal heart attacks.
5. Publicly available ambient air quality monitoring should be conducted at Lithgow and Wyee, which are communities with power stations but no current air monitoring.
6. Data quality assurance should be implemented for the National Pollutant Inventory.
7. The health impacts of electricity generation in other Australian states should be investigated.

The problem

The health effects of air pollution have been known about since the middle of the 20th century and the list of health problems to which air pollution contributes now includes heart disease, stroke, asthma attacks, low birth weight of babies, lung cancer and type 2 diabetes.

The form of pollution that has the most convincing evidence of harm and the strongest effect is fine particles with an aerodynamic diameter of up to 2.5 microns ($PM_{2.5}$). The major sources of these in the Sydney Greater Metropolitan Region are burning coal for electricity, burning oil for transport, and burning wood for home heating or during bushfires.

Coal-fired power stations produce particles of two kinds: the primary particles that are released as coal is burnt, and secondary particles that form in the atmosphere from the sulfur dioxide (SO_2) and oxides of nitrogen (NO_2 and NO, referred to as NO_X) gases released during combustion. Particle air pollution is described by size classes, as their size dictates where they end up in the human respiratory system. Larger particles are trapped in the nose and upper airways, but the finest particles reach to the air sacs deep in the lungs and even enter the blood stream, causing systemic effects.

Technologies exist to capture particles, NOx and SO_2 pollutants rather than releasing them to the environment, but the use of these technologies is rare in Australia despite being required in most other countries. All New South Wales power stations have fabric filters that effectively capture primary particles, but all Victorian stations and most Queensland stations have only electrostatic precipitators, which are much less effective. No power station in Australia has post-combustion desulfurisation to remove SO_2 or selective catalytic reduction to remove NOx, only some have special furnace designs to reduce NOx production, and none has mercury controls. Australia's power stations therefore emit much higher concentrations of these pollutants than those in most other countries.

From the 1930s, electricity demand rose steeply, and coal-fired power stations were built to support the expanding distribution grid and tram/train operations. In Sydney these were at Ultimo, Balmain, Pyrmont, White Bay and Matraville, all close to the centre of the city. As these old generators reached the end of their life between 1963 and 1983, sites were chosen for new power stations, ten times as big. These sites were located away from Sydney so the city's population of 3 to 4 million people would not be exposed to the stack emissions.

Since that time, the science of air pollution has developed substantially. Using modern methods, it is now apparent that pollution from the current coal-fired power stations travels long distances and blows back to contaminate the air in Sydney despite the power stations being 90, 98 and 155 km away.

The objective of this report is to estimate the health impact of emissions from current electricity generation so that the community can better understand what they are being exposed to, and so that decision makers can include health implications of sources of generation in planning the future electricity supply. This analysis uses the best published estimates of the components of air pollution, the risks of disease and the population exposures as at the time of writing, recognising that there currently exists varying degrees of uncertainty about some of these inputs.

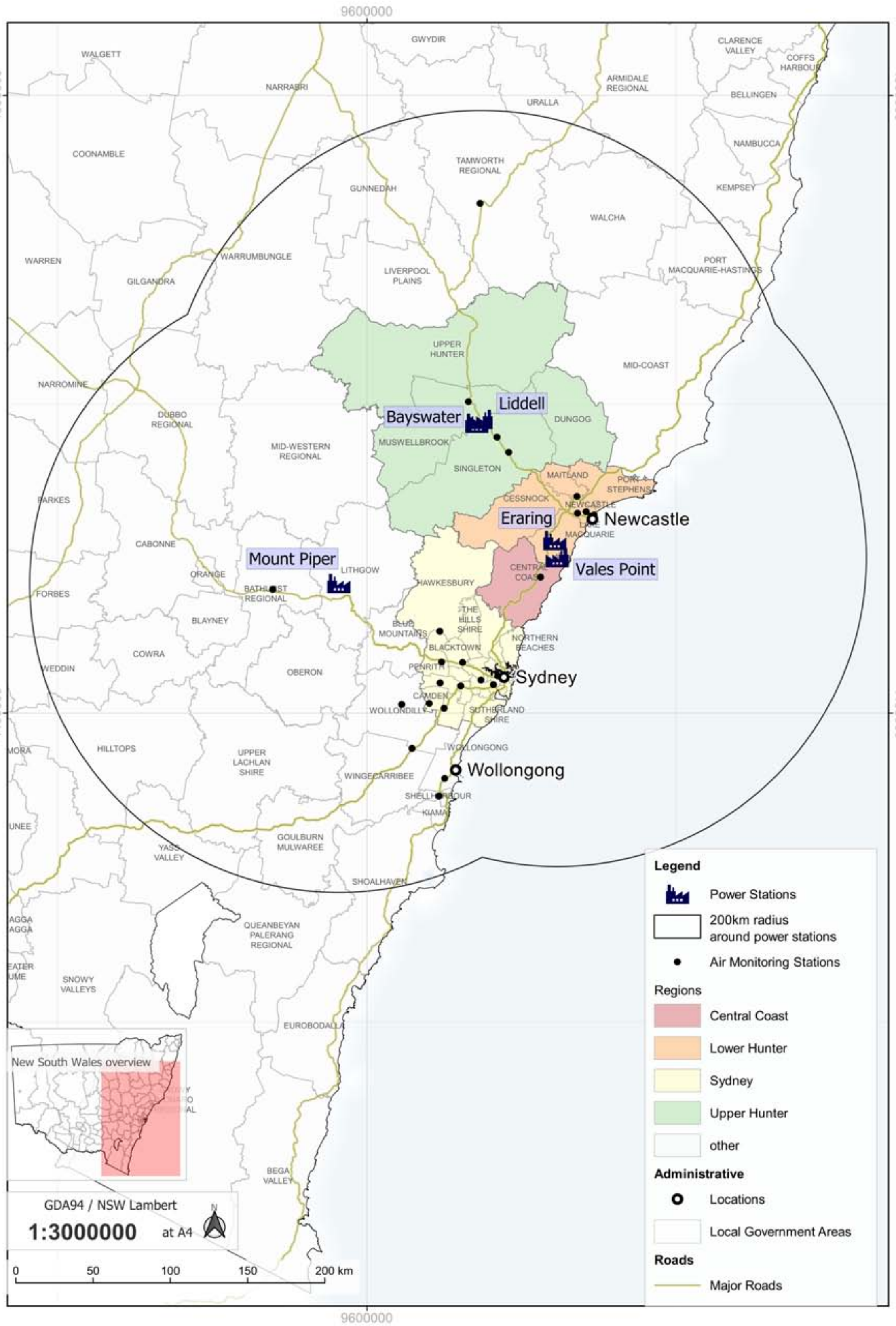
Selection of regions for analysis

New South Wales has 128 local government areas (LGAs) with population sizes ranging from 1,914 in Brewarrina to 354,960 in Canterbury-Bankstown, of which 71 LGAs are within 200 km of a coal-fired power station. The population of NSW is heavily concentrated in the cities of Sydney, Newcastle and Wollongong, with medium densities along the rest of the coast, and low numbers inland. Regions were defined for this work according to airsheds and locations where the air quality has been studied, as shown in Table 3. The remainder group is all the LGAs for which the main town is within 200 km of a coal-fired power station. The distance to the main town has been used, rather than the area centroid, as the population is highly concentrated in the towns. The remainder region extends from Taree in the North to Kiama in the South and Forbes in the West. The 71 LGAs chosen for this analysis have a total population of 6.5 million, which is 86% of the NSW state total. A full list of LGAs is at Appendix 3.

Table 3: Regions for analysis

	Sydney	Central Coast	Lower Hunter	Upper Hunter	Remainder	Total study area
Number of LGAs	31	1	5	4	30	71
Population	4,459,948	333,119	568,300	65,004	1,136,238	6,562,609
Number of monitors	11	1	6	3	8	29
Particle characterisation	yes	no	yes	yes	no	
Meteorological traceback	yes	no	no	no	no	

Figure 1: The regions used for analysis, showing power station and air monitor locations.



The power stations of NSW

There are five operating coal-fired power stations in NSW, which together produced 55.7 terawatt hours (TWh) of electricity in 2016–17, being 86% of generation in the state. One station is located at Lithgow west of Sydney, two are at the southern end of Lake Macquarie on the Central Coast, and two are at Muswellbrook in the Upper Hunter Valley.

The pollution emissions from each power station are reported to the National Pollutant Inventory, as shown in Table 4 below.

It will be noted that the mass of the gases that lead to secondary particles greatly exceeds the mass of primary particles. Once in the atmosphere the gases undergo chemical transformation and contribute to the formation of secondary particles, a process that takes time, during which the pollution may have been carried long distances by prevailing winds. These distances have been recorded in Asia where fine particles at Dhaka originated as smoke in Iran and Iraq having travelled 2,200 to 5000 km. (Begum et al., 2011).

Table 4: 2017 electricity emissions of NOx, SO_2 and fine particles from NSW coal-fired power stations

Power station emissions (tonnes)	NOx	SO_2	Primary $PM_{2.5}$
Bayswater, Upper Hunter	32,214	50,271	294
Liddell, Upper Hunter	18,627	33,490	183
Eraring, Central Coast	18,555	30,533	148
Vales Point, Central Coast	21,008	16,000	71
Mount Piper, Lithgow	22,021	32,000	59
Total emissions from power stations	**112,425**	**162,294**	**755**
NSW emissions, all sources	**280,000**	**190,000**	**3,900**

Attributing particles to sources

For pollution to have a human health impact there must be a pathway from the source to the person – from up the smoke stack to down the trachea.

For Sydney, the composition of fine particle air pollution has been intensively studied and is well understood, so the contribution from various sources is established (Cohen, Crawford, Stelcer, & Atanacio, 2012). Both particle characterisation and meteorological back tracking has been done for Richmond, on the western outskirts of Sydney. As this site is a long way from the power station sources, the Richmond results are assumed to apply to the whole of Sydney, and there is a good level of certainty about the results.

The Sydney Particle Characterisation Study 2016, published by the Australian Nuclear Science and Technology Organisation (ANSTO) and the NSW Environment Protection Authority (NSW EPA), identified seven fingerprints, of which two, mixed secondary sulfate and mixed-ind-saged, contain the secondary particles derived from coal combustion. At the four sites reported there was not much variation in the proportion of total $PM_{2.5}$ comprised of these components, as shown in Table 5. While the back trajectories have only been reported from Richmond, it is safe to assume that the results would be the same across the Sydney basin, as the power stations are a long distance away (90 to 155 km) and variations in wind direction would distribute the secondary particles.

Table 5: Characterisation of fine particles from four Sydney sites, proportion of total $PM_{2.5}$

Site	Mixed 2^{nd} sulfate	Mixed ind-Saged	Sum of these fingerprints
Lucas Heights	30%	9%	39%
Richmond	26%	15%	41%
Mascot	20%	23%	43%
Liverpool	22%	14%	36%

Abbreviations: mixed secondary sulfate (mixed 2^{nd} sulphate), mixed industrial aged salt (mixed ind-Saged)

The background non-anthropogenic (naturally occurring) $PM_{2.5}$ is estimated to be 2.5 µg/m^3, and the Sydney particle characterisation study included measuring the background particles, so these proportions are of total $PM_{2.5}$, not just anthropogenic particles.

Understanding electricity units

The unit of electricity on domestic power bills is the kilowatt hour (KWh). A total of 1,000 of these units is called a megawatt hour (MWh), which is the unit used for electricity pricing in the wholesale market.

1 kilowatt hour (KWh)
The standard unit of electricity on domestic power bills

1,000 KWh = 1 megawatt hour (MWh)
A megawatt hour is the standard unit used for market pricing on wholesale market

1,000 MWh = 1 gigawatt hour (GWh)

1,000 GWh = 1 terawatt hour (TWh)

Particle characterisation and meteorological back tracking

Dr David Cohen and others from Australian Nuclear Science and Technology Organisation have done extensive work to characterise the fine particles at various locations in NSW and published papers such as *Application of positive matrix factorisation, multilinear engine and back trajectory techniques to the quantification of coal-fired power station pollution in Sydney* (Cohen, Crawford et al. 2012).

In summary, samples of fine particles were collected two days per week over many years in a high-volume sampler, onto 25mm Teflon filters, giving 912 days for analysis. Ion beam analysis and laser absorption methods were used to identify 21 elements in the collected particles, then a statistical method of Positive Matrix Factorisation was used to identify source fingerprints within the temporal variation between days. The 'best fit' solution had seven fingerprints and explained 98% of the total particle mass.

The identified fingerprints are:

Factor		% of $PM_{2.5}$
1	Secondary sulfate: The most common element is sulphur, which originates from motor vehicles, coal, and other industry.	27.3
2	Wind-blown soil: aluminium, silicon, calcium, titanium, iron.	4.76
3	Sea Salt: Sodium Chlorine, Bromine.	5.54
4	Aged industrial sulfur: sodium, sulfur, and black carbon. Formed by an interaction of sea salt with industrial sulfur pollution.	12.4
5	Smoke: biomass burning. hydrogen, potassium, black carbon.	37.1
6	Industry: black carbon, iron, zinc.	1.75
7	Automobiles: hydrogen, black carbon, trace elements.	11.2

After deriving the fingerprints, a subsequent method of atmospheric modelling back trajectories was used to determine the proportion of factors 1 and 4 from power generation. This used 21,888 hourly wind data records from the sampling days to trace back where each parcel of air had been each 30 minutes over the last five days prior to being sampled at Richmond. After further statistical analysis, the authors concluded that Factor 1 from coal-fired power stations contributes 10% to 13% of total $PM_{2.5}$ and Factor 4 from power stations contributes 4% to 6% of $PM_{2.5}$, for a total power station contribution to fine particle air pollution at Richmond they report as 14% to 18%.

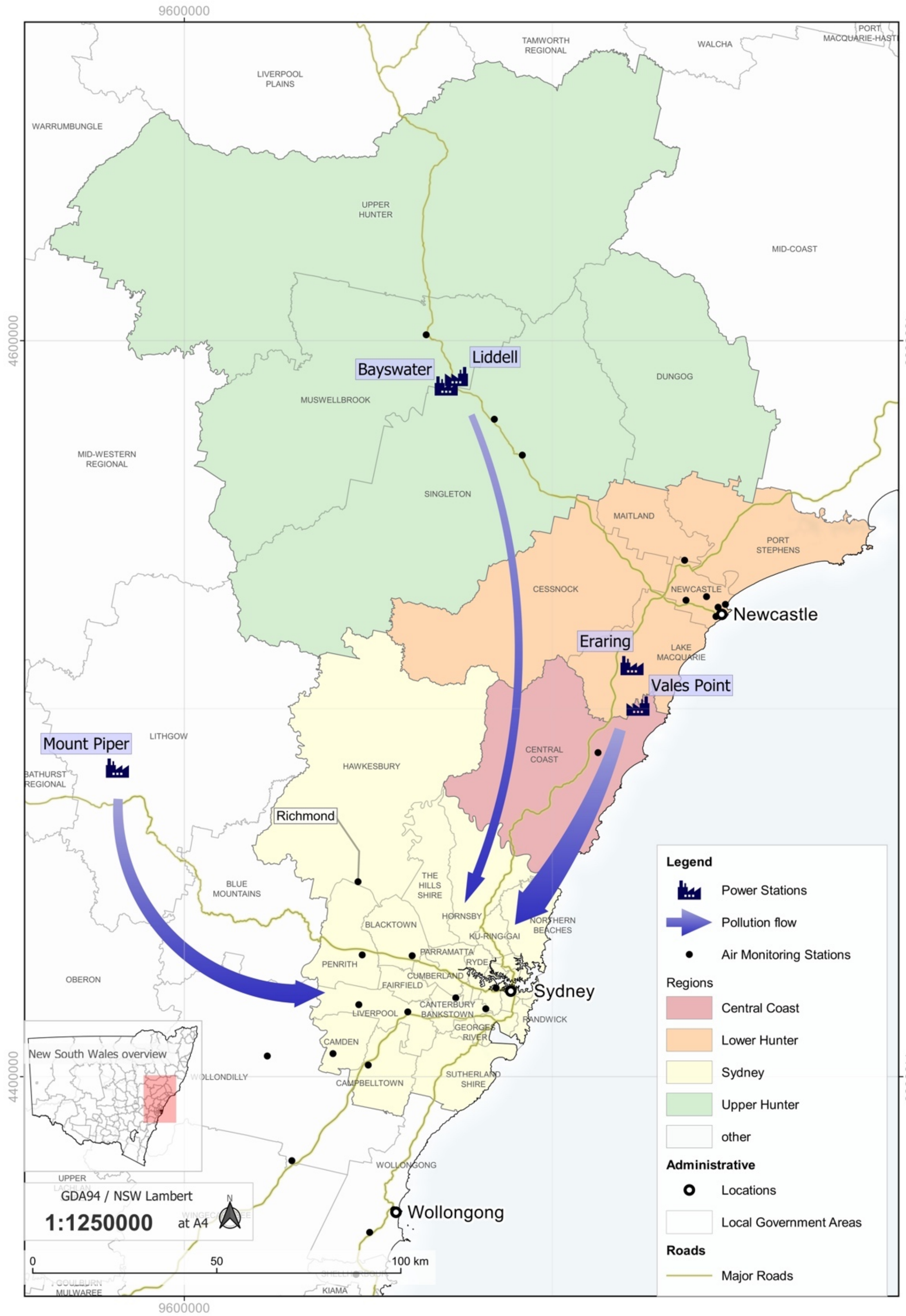
When this analysis was done, there were eight coal-fired power stations in NSW, of which three have since closed one each from Lithgow, Central Coast and Hunter Valley. The remaining stations are running at higher capacity factors, so sulfur emissions have hardly changed.

For the Upper and Lower Hunter Valley, particle characterisation has been done identifying primary and secondary particles in ambient air, but not meteorological back tracking.For these regions, the contribution from electricity generation in this analysis is based on the National Pollutant Inventory (NPI) of emissions to air of the gases that lead to secondary particle formation, assuming that the amount that ends up in ground level ambient air is equal from all sources. This is a reasonable basis for attribution of particles to sources, but not as certain as meteorological back tracking.

The Central Coast has had no particle characterisation work done and has only one monitor. As it shares the same two power stations with the Lower Hunter airshed and has similar NPI data, the electricity industry contribution to Central Coast particle composition is conservatively assumed to be the same proportion as the Lower Hunter. The attribution of particle sources for the Hunter regions and the Central Coast is regarded as having a medium level of certainty. No particle characterisation work has been done for the remainder areas, so for these LGAs we must rely on estimates that are necessarily less certain.

The existence of uncertainty about the composition of fine particles and the exact contribution from coal combustion in some areas is not a reason to ignore the problem, so in this report results for Sydney are regarded as high certainty, the Hunter Valley and Central Coast as medium certainty, and remainder areas as low certainty.

Figure 2: Pollution transport from the Central Coast occurs most frequently, followed by that from Lithgow.



Health outcomes assessed

Three health outcomes were chosen for this analysis on the basis of having strong evidence from cohort studies, or meta-analyses of cohort studies, that they are caused by long-term fine particle air pollution. Other health outcomes that are related to short-term exposure such as asthma attacks, exacerbations of chronic lung disease or myocardial infarction were not included, as the power station contribution to short-term exposure has not been measured. Likewise, effects of ozone, mercury and direct NOx or SO_2 gas exposure were not included, and these health burdens would be additional to those assessed in this analysis.

All-cause mortality

Exposure to fine particle pollution causes increased risk of death, which is mostly from heart attacks and strokes, although cancers also contribute. Attempts to identify the lower limit of exposure for which there is any risk have not defined a safe level of exposure, so current scientific opinion is that the risk extends right down to near zero. A small amount gives a small risk, and a large amount gives a large risk, right across the range. The best estimate of risk for all-cause mortality is relative risk (RR) of 1.06 per 10 μg/m^3, derived from the long-term follow up of the American Cancer Study (Krewski, Jerrett, Burnett, Ma & Hughes, 2009) and applies to adults aged 30 and above.

Diabetes

Diabetes, defined as the inability to regulate glucose metabolism, occurs in three forms known as type 1, type 2 and gestational diabetes. Type 1 and type 2 have quite distinct pathophysiology and causes, so should be considered different diseases. There has long been thought to be a role for systemic inflammation in the causation of type 2 diabetes, so associations with air pollution exposure have been examined. A systematic review of the published literature up to 2014 found seven studies that could be combined in quantitative meta-analysis, and estimated a summary RR of 1.10 (95% ci 1.02 to 1.18) per extra 10 μg of $PM_{2.5}$.(Eze et al., 2015). These studies were all conducted in Europe and North America where air quality is more like Australia than would be found in Asian countries.

More recently, a large and definitive study has been conducted in North America with a sample of 1.7 million US veterans (Bowe et al., 2018). This study is convincing because it has a very large sample size, a good characterisation of demographic confounders, studied new cases (incident) rather than prevalent diabetes, and included both a positive and a negative control condition. The positive control was that the air exposure was, as expected, associated with all-cause mortality, and the negative control showed that air pollution was not associated with leg fractures. The use of such controls demonstrates that adjustment for confounding has been correctly applied. The concentration-response function showed that an extra 10 μg/m^3 of $PM_{2.5}$ was associated with a hazard ratio 1.15 (1.08, 1.22) for incident type 2 diabetes.

The background incidence of type 2 diabetes was measured in the Blue Mountains Eye study and shown to be 0.9% per year in people over 49 years of age (Barclay, Flood, Rochtchina, Mitchell, & Brand-Miller, 2007)[1].

Birth weight

The most convincing evidence for an effect of air pollution comes from China where during the Beijing Olympics in 2008 extraordinary measures were put in place to reduce air pollution during the six weeks of the games (Rich et al., 2015). Cars and trucks were heavily restricted, and many industries including a steel works and four coal-fired power stations were closed for the duration. Comparison of the weights of babies born during the clean air weeks, compared to the same weeks in 2007 and 2009 showed an average 23 g increase. Every one of those babies is set up for slightly better health during their life, as good birth weight is associated with less risk of many childhood and adult illnesses. The mechanism by which air pollution affects foetal growth is thought to be via effects on the foetal thyroid, (Janssen et al., 2017) or by changing placental vascular resistance (Carvalhoa et al., 2016).

The Beijing evidence is convincing, but the clean air month was a reduction from ten times Australian values to five times (Reuters, 2018). Exposures more like Australian levels were studied in the ESCAPE cohorts (Pedersen, 2013) with pooled data from 14 cohorts in 12 countries. This showed an adjusted odds ratio (OR) of 1.18 (1.06–1.33) per 5µg $PM_{2.5}$ for birth weight less than 2,500 g in full-term babies born after 37 weeks in the full cohort, and the value 1.18 is used in this analysis. The risk, however, was higher at OR 1.41 (1.20-1.65) in the subset with exposure less than the European standard at the time of 20 µg/m^3. Australian exposure values are all lower than 20 µg/m^3 so this later value has been used in a sensitivity analysis.

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[1] The Bowe C-R function is chosen because it is based on diabetes incidence rather than prevalence, in a well characterised cohort with detailed air exposure records, from geographic areas where the air is not too different to Australia.

The background incidence value from Barclay misses some type 2 diabetes in younger people, but the incidence rises steeply with age, so this estimate will give a more accurate result than the alternate estimate from AusDiab which found 0.8% per year in people aged over 25 years. There are many measurements of prevalence by small geographic area, but few of incidence so this one value was applied across all LGAs.

Methods

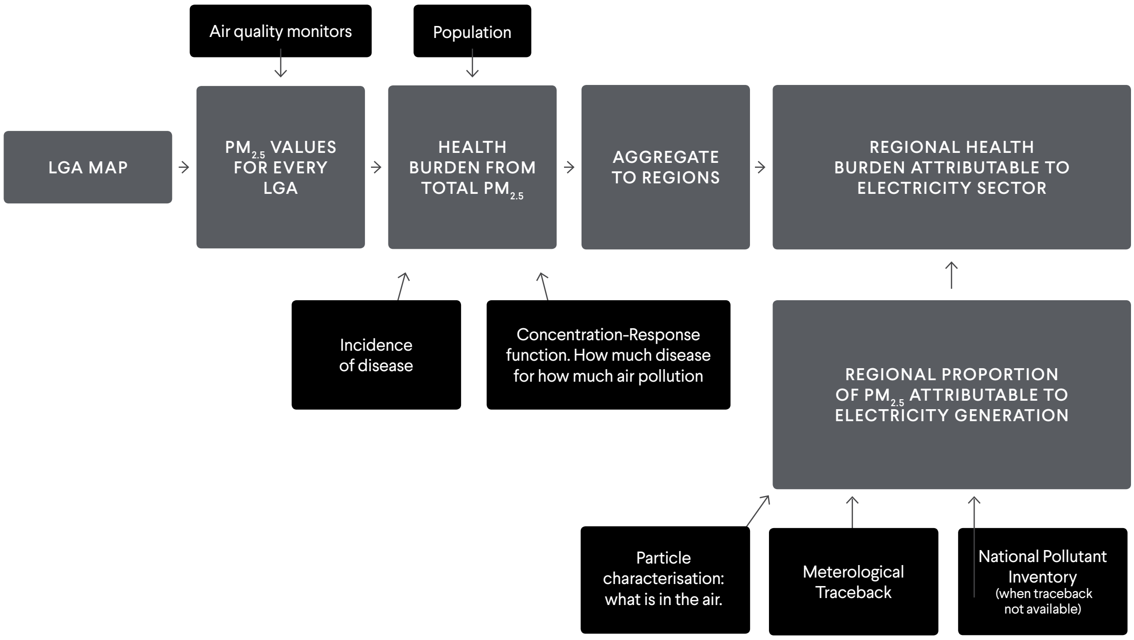
Health impacts were calculated using the software BenMap-CE version 1.3 published by the United States Environmental Protection Agency, using a map grid based on local government area (LGA) boundaries. There are 128 LGAs, of which 71 are within 200 km of one of the power stations. Air values for each LGA were derived by Voroni neighbourhood averaging, with a maximum distance of 200 km, using the inverse square method.

The health impact function (1-1/exp (beta*delta air))*incidence *population was used to estimate the proportion of incidence attributable to air exposure. Beta is the natural logarithm of the hazards ratio from the original epidemiology. For birth weight and diabetes, the BenMap analysis procedures were replicated in Microsoft Excel using the equivalent formula: $\left(1-\frac{1}{HR^{\frac{\Delta}{U}}}\right) * population * incidence$ where delta is the change in air exposure in μg/m^3, U is the units for the published Hazard Ratio, usually 5 or 10 μg/m^3, and HR is the hazard ratio.

A total burden attributable to fine particle pollution was established by summing LGAs across regions, then multiplying by the proportion of fine particles attributable to electricity generation for each region to give the industry-specific burden. The analysis is shown in Figure 3 below.

The further step of interpreting a mortality estimate as Years of Life Lost (YLL) is based on the NSW life tables from the Australian Bureau of Statistics. Deaths at typical ages are multiplied by life expectancy at those ages to give YLL, which is a useful input for economic assessment.

Figure 3: Steps and inputs in analysis



Air data

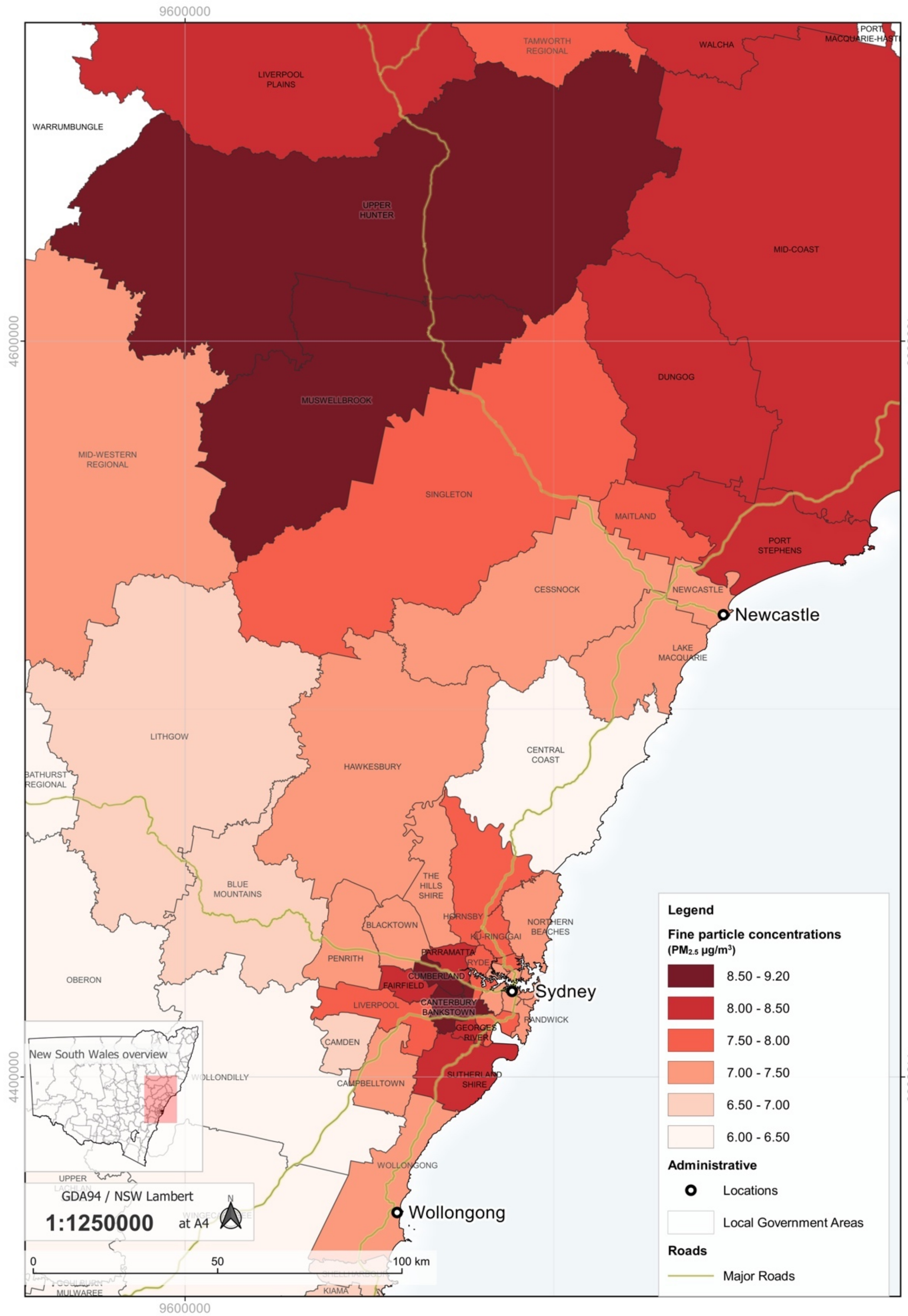
Ambient air data for 2017 year was obtained from 29 monitors run by the NSW Office of Environment and Heritage (OEH). These monitors use Beta Attenuation (BAM) methods, and a single annual average value for each monitor was downloaded from the OEH web portal. The monitor at Stockton was excluded from analysis, as this monitor frequently records high values due to sea salt because it is located only 430 metres from the coast. Monitors that record values more representative of population exposure are located at Newcastle, Carrington and Mayfield within a few kilometres. The analysis is based on 28 monitors.

Proportions of fine particle exposure due to electricity generation

Sydney

The results published by Cohen 2012 establish that the proportion of Sydney $PM_{2.5}$ attributable to electricity generation is between 14% and 18%. Since that work was done three power stations, one each from the Hunter Valley, Lithgow and the Central Coast, have closed, but the remaining plants have been operating at higher capacity factors.

Figure 4: Local government areas showing $PM_{2.5}$ levels derived from monitoring conducted by the NSW Environmental Protection Authority.



Upper and Lower Hunter Valley

Particle characterisation studies, but not meteorological back tracking, has been conducted in the Upper Hunter and Lower Hunter, with reports published in 2013 and 2016 respectively (Hibberd et al., 2016; Hibberd, Selleck, Cohen, Stelcer & Atanacio, 2013). The Upper Hunter study identified eight factors, or classes of particles, three of which include contributions from coal combustion. The extra factor beyond the Sydney study is of secondary nitrate particles. The largest single factor in Muswellbrook is smoke from wood heating at 30% and, as shown in Table 7, the sum of the factors attributable to electricity generation is 37.2%. The wood smoke factor at Muswellbrook is probably exaggerated by the monitoring site being in a residential street in close proximity to housing. In Singleton, with similar climate and demographics, the monitor site is further from housing and showed wood smoke at 14% of $PM_{2.5}$.

The factors that include contributions from electricity generation are factor 3: secondary sulfate, factor 5: industry aged sea salt, and factor 8: secondary nitrate. The factors are described in quotes from the *Upper Hunter Valley Particle Characterisation Study* (Hibberd et al., 2013), as follows.

Air pollution factors contributed to by coal combustion

Factor 3
Secondary Sulfate

Factor 3 contributes 17% to the $PM_{2.5}$ mass at Muswellbrook and 20% at Singleton. The factor is dominated by secondary ammonium sulfate with the factor accounting to 60% of the sulfate and 85% of the ammonium in the samples.

Ammonium and sulfate occur in atmospheric particles as a result of photochemical reactions in the atmosphere. Gaseous sulfur dioxide (SO_2) is emitted to the atmosphere during combustion of fossil fuels (e.g. in power stations or motor vehicles) and in the presence of sunlight will oxidise to form sulfuric acid (H_2SO_4), which is a strong acid. The seasonal cycle displayed by the contribution of this factor to $PM_{2.5}$ mass in Figure 29 of higher contributions during the summer months represents the greater time for photochemical reactions to occur during the summer months. The only significant gaseous base in the atmosphere is ammonia which is globally derived from biological production, such livestock wastes and fertiliser. It plays an important role in neutralising acids in the atmosphere, hence readily neutralises the sulfuric acid to produce ammonium sulfate aerosol.

The CPF plots (Figure 30) both have lobes to the north and south. This does not correspond to the major source of SO_2 in the region (the power stations) but reflects the fact that the chemical reactions to form the $(NH4)_2SO_4$ take time to occur (Hibberd et al., 2013).

Factor 5
Industry-aged sea salt

The average contribution of Factor 5 to $PM_{2.5}$ is 18% at Singleton and 13% at Muswellbrook. This factor consists of Na^+, Mg^{2+}, SO_4^{2} and with almost no Cl. This source is identified as industry aged sea salt as the

	[Na^+/Mg^{2+}] ratio is the same as that of sea salt with the Cl displaced as HCl mostly by the acid H_2SO_4 and to a lesser extent nitric acid (HNO_3). As discussed in Section 6.3, the source of H_2SO_4 the oxidation of SO_2 emitted from fossil fuel combustion, so the seasonal cycle displayed by the contribution of this factor to $PM_{2.5}$ mass in Figure 37 of higher contributions during the summer months represents the greater time for photochemical reactions to occur during the summer months. In this case however, H_2SO_4 is neutralised by the weak base of the sea salt particles resulting in the replacement of Cl by SO_4^{2} (Hibberd et al.,2013). The acid component in this reaction is either H_2SO_4 from SO_2 or HNO_3 from NO_2, both of which are released in substantial quantities by coal combustion, as detailed in NPI releases in Table 4.
Factor 8 Secondary nitrate	*The average contribution of Factor 8 to $PM_{2.5}$ is 3% at Singleton and 8% at Muswellbrook. This factor contains most of the NO_3 and includes some NH_4+, Cl, Na+, and Organic Carbon. Nitrate occurs in atmospheric particles as a result of photochemical reactions in the atmosphere. NO_2 is emitted to the atmosphere during combustion of fossil fuels (e.g. in power stations or motor vehicles) and in the presence of sunlight will oxidise to form HNO_3 (nitric acid). Nitrate is neutralised by the gaseous base ammonia* (Hibberd, et al., 2013).

The proportion of these particles derived from electricity generation is based on power station emissions divided by total emissions within a 50 km radius as reported to the National Pollutant Inventory shown in Table 6.

Table 6: Emissions to air from the 2016–17 National Pollutant Inventory

	Upper Hunter: NPI Muswellbrook 50 km radius	Lower Hunter:NPI Maitland 50 km radius	Central Coast: NPI Wyong 50 km radius
Total SO_2	**83,800 tonnes (t)**	**57,600 t**	**46,700 t**
Electricity SO_2	83,800 t	46,500 t	46,600 t
Proportion	100%	80.7%	99.8%
Total NOx	**71,800 t**	**48,000 t**	**41,400 t**
Electricity NOx	51,000 t	39,800 t	39,700 t
Proportion	71.0%	82.9%	95.9%

For the Upper and Lower Hunter, a figure was calculated for the proportion of all $PM_{2.5}$ which can be attributed to power station emissions by averaging the proportions of each factor across the two sites for the Upper Hunter and three sites for the Lower Hunter, then multiplying this by the proportion of contributing gases from the NPI record. For instance for the Lower Hunter, secondary sulfate was observed to be 12%, 10% and 8% of $PM_{2.5}$, with average value of 10%, multiplied by 0.807 which is the (NPI) regional proportion of SO_2 which comes from power stations, so 8.07 % of regional $PM_{2.5}$ is secondary sulfate from power stations. As shown in Tables 7 and 8, 37.2% of fine particles in the Upper Hunter and 34.1% in the Lower Hunter can be attributed to the electricity sector.

Table 7: Upper Hunter proportion of $PM_{2.5}$ attributable to electricity generation, from Upper Hunter particle characterisation study and NPI emissions

Factor	Singleton % of $PM_{2.5}$	Muswellbrook % of $PM_{2.5}$	Proportion attributable to electricity (%)	Upper Hunter attributable proportion (%)
Factor 3 Secondary sulfate	20	17	100	18.5
Factor 5 Industry aged sea salt	18	13	100	15.5
Factor 8 Secondary nitrate	3	6	71	3.2
Total				**37.2**

Table 8: Lower Hunter proportion of $PM_{2.5}$ attributable to electricity generation, from Lower Hunter particle characterisation study and NPI emissions

Factor	Newcastle % of $PM_{2.5}$	Beresfield % of $PM_{2.5}$	Mayfield % of $PM_{2.5}$	Proportion attributable to electricity (%)	Lower Hunter attributable proportion (%)
Factor 3 Secondary sulfate	12	10	8	80.7	8.1
Factor 5 Industry-aged sea salt	23	23	25	80.7	19.1
Factor 8 Secondary nitrate	8	6	11	82.9	6.9
Total					**34.1**

Central Coast

The two large coal-fired power stations at the Southern end of Lake Macquarie are only 11 km from each other, but Eraring is in Lake Macquarie LGA categorised as Lower Hunter region and Vales Point is in Central Coast LGA categorised as Central Coast region. The Central Coast has had neither particle characterisation nor metrological back tracking done.

Taking Wyong as the centre of population, there are 92 facilities reporting to the NPI in a 50 km radius, and as shown in Table 6 there are substantial quantities of SO_2 and NO_2 released within the region. The majority of the population of the Central Coast lives closer to the power stations than the population of the Lower Hunter, so as a conservative assumption the Lower Hunter attributable proportion, 34.1%, was used for the Central Coast.

Remainder

The contribution of electricity generation to the particles in the air for all other LGAs is unknown, but cannot be assumed to be zero. The distance from power stations ranges from zero km at Lithgow LGA to 200 km for peripheral areas. The value for the proportion attributable to electricity generation is assumed to be the same as the midpoint estimate for Sydney of 16%, but the associated health burden is regarded as being of low certainty.

Health inputs

Population data for each LGA in five-year age groups originating from the Australian Bureau of Statistics was retrieved from NSW (Centre for Epidemoilogy and Evidence, 2018), Mortality data for each LGA was from Australian Bureau of Statistics, and used to derive a crude all-age mortality rate. This was adjusted to an estimated 30 to 99 year mortality rate based on data for the whole of Australia from the Australian Institute of Health and Welfare. The number of births in each LGA was provided by NSW Health, and the incidence of low birth weight was available only at the level of the 16 local health districts, so each LGA was allocated the low birth weight incidence of the health district to which it belongs. LGAs fit neatly into Local Health Districts (LHDs) except for the City of Sydney, i.e. the CBD, which straddles two LHDs. Diabetes incidence was based on follow up of the Blue Mountains Eye Study, as while there are many published estimates of diabetes prevalence there are few for incidence. The incidence of 0.9% per year applies to people over the age of 50.

Timing

The latest available population and incidence data was for 2015, however air quality for 2017 has been used, as several new monitoring locations were established during 2016. This gives more detailed air exposure. There were no major trends in air or population values from year to year, so combining 2015 population with 2017 ambient air is justified.

Results

Mortality

It must be remembered that no person's death certificate states that they died of air pollution. This analysis uses observed pollution exposures and estimates how many deaths would be expected given what is known about the degree of risk per amount of exposure. Using the midpoint estimate for Sydney, the total annual mortality burden from coal-fired power is 279 (95% ci 190, 367) premature deaths at typical ages per year. This assumes a steady state, i.e. the people suffering adverse health effects this year have cumulative exposure over many years. It is uncertain how rapidly health benefits would accrue if improvements to air quality could be achieved. The causes of death exacerbated by air pollution, mostly heart disease and stroke, tend to affect older people, so the mortality burden can alternately be understood as 2,614 (95%ci 1,780, 3,438) Years of Life Lost.

Table 9: Premature deaths per year attributable to the fine particle pollution from electricity generation in NSW

	Sydney	Central Coast	Lower Hunter	Upper Hunter	Remainder	Total
Population aged 30-99	2,657,209	211,514	350,056	38,649	714,658	**3,972,086**
Pop weighted Average $PM_{2.5}$ µg/m^3	7.7	6.1	7.4	8.4	6.8	
Proportion of $PM_{2.5}$ from electricity generation	16%	34%	34%	37%	16%	
All deaths aged 30 -99	21,709	2,065	3,555	383	6,824	**34,536**
Deaths attributable to fine particle air pollution (95% confidence interval)*	959 (653,1260)	72 (50,95)	151 (103,198)	18 (12,24)	269 (183,353)	**1469 (1001,1930)**
Deaths attributable to electricity generation	153 (104,202)	25 (17,32)	51 (35,66)	7 (4.6, 8.9)	43 (29,56)	**279 (190,367)**
Years of Life Lost	1,433	234	477	65	402	**2,614**
Certainty for mortality estimate	high	medium-low	medium	medium	low	

Note: Numbers in brackets are the 95% confidence interval derived from the concentration-response function.
*Confidence interval based on the C-R function

Birth weight

Annually there are 233 babies born weighing less than 2,500 g each year due to air pollution from power generation as shown in Table 10. Observational research indicates that the last months of gestation are the most sensitive. Improved birth weights would be expected within one to three months of improvements to air quality.

Table 10: Babies born each year weighing less than 2,500 g attributable to the fine particle pollution from electricity generation

Region	Sydney	Central Coast	Lower Hunter	Upper Hunter	Remainder	**Total**
Pop weighted average $PM_{2.5}$ µg/m^3	7.7	6.1	7.4	8.4	6.8	
Proportion from electricity generation	16%	34%	34%	37%	16%	
Number of births	63,042	3,880	6,937	862	12,595	**87,316**
Number of low birthweight babies	4,035	252	499	62	838	**5,686**
Low birth weight attributable to $PM_{2.5}$ (95% ci)*	918 (351,1447)	46 (17,74)	109 (41,173)	15 (6,24)	170 (65,271)	**1,258 (480,1989)**
LBW attributable to electricity generation (95% ci)*	147 (56,232)	16 6,25)	37 (14,59)	6 (2, 9)	27 (10,43)	**233 (88,368)**
Certainty	high	medium-low	medium	medium	low	

*ci = Confidence interval, based on the odds ratio from the observational epidemiology.

Diabetes

Of the expected 19,257 people newly diagnosed with type 2 diabetes each year, 361 can be attributed to air pollution originating in electricity production. It is unknown how long the lag is between particle exposure and diabetes development.

Table 11: New cases of type 2 diabetes

	Sydney	Central Coast	Lower Hunter	Upper Hunter	Remainder	Total
Number of people over age 50	1,339,278	130,959	206,124	21,174	442,028	**2,139,563**
Expected number of new cases of diabetes	12,054	1,179	1,855	191	3,978	**19,257**
Number attributable to $PM_{2.5}$ exposure (95% ci based on the hazard ratio.)	1,241 (700,1726)	96 (54,134)	183 (103,255)	21 (12,29)	365 (206,509)	**1,906 (1075,2653)**
Diabetes cases attributable to electricity generation (95% ci based on the hazard ratio)	199 (112,276)	33 (18,46)	63 (35,87)	8 (4,11)	58 (33,81)	**361 (202,501)**

Sensitivity analysis

As there are varying degrees of uncertainty around the estimates of the power station contributions to fine particle concentrations, these were varied in a sensitivity analysis. The values for Sydney were tested at the ends of the range reported from the original work; 14% and 18%, the values for the Lower and Upper Hunter were tested at plus and minus 10%, the values for the Central Coast varied by 20% and for remainder regions tested at plus 100% and minus 50%. Results are displayed in Table 12.

Table 12: Sensitivity analysis results reflecting uncertainty about the proportion of $PM_{2.5}$ attributable to power generation; number of outcomes per year

Outcome	Lower	Midpoint	Upper
Mortality	228	279	362
Low birth weight	353	426	540
Diabetes	293	360	470

The source for the risk estimate for low birth weight gave a higher value for the subset of cohorts where air exposure was less than the WHO standard at the time of 20 $\mu g/m^3$. As this exposure is closer to observed NSW values, the higher risk estimate may be appropriate here. Table 13 shows Table 10 recalculated for OR 1.41 (1.20, 1.65) as reported by Pedersen 2013. The point estimate of 558 shows a substantial burden of low birth weight babies if the higher odds ratio is correct for the Australian context.

Table 13: Sensitivity analysis for low birth weight using the ESCAPE results for populations with annual $PM_{2.5}$ less than 20 μg/m³

Region	Sydney	Central Coast	Lower Hunter	Upper Hunter	Remainder
Pop weighted Average $PM_{2.5}$	7.7	6.1	7.4	8.4	6.8
Proportion from electricity generation	16%	34.1%	34.1%	37.2%	16%
Number of births	63,042	3,880	6,937	862	12,595
Number of low birthweight babies	4,035	252	499	62	838
LBW attributable to $PM_{2.5}$ (95% ci)	1,672 (998, 2184)	86 (50, 115)	200 (119, 262)	27 (16, 35)	315 (186, 416)
LBW attributable to electricity generation (95% ci)	268 (160, 349)	29 (17, 39)	68 (40, 89)	10 (6, 13)	50 (30, 67)
Certainty	high	medium	medium	medium	low

Potential weaknesses of the health burden analysis

Potential weaknesses of this analysis include the necessity to rely on assumptions about the contributions of electricity generation to pollution in areas where these have not been measured. The greatest burden for each health outcome is for the Sydney region where there is the most certainty. The level of uncertainty has been tested in a sensitivity analysis and the health burden remains substantial even at the lower estimates.

The authors of the Upper and Lower Hunter particle characterisation studies did not describe a proportion from power stations, and the results had to be combined with figures from the National Pollutant Inventory (NPI). These figures are provided by self-report from industry and are unaudited. There are sometimes unexplained anomalies in the NPI data such as sudden year-to-year variations in declared amounts, so a lack of validity from NPI could affect this work. Using the emissions inventory data also assumes that all regional sources of SO_2 or NOx are equally likely to end up forming secondary particles in ambient air.

The low certainty of the remainder region is based on tenuous interpolation of results from distant air quality monitors, and no observations of particle characteristics. The results for the remainder region should be regarded as indicative, but are the best possible until further monitoring and analysis of air quality for those areas is carried out.

Attributing health burdens to individual power stations

Attributing health impacts to individual power stations is now possible following the publication in 2018 of analysis in which Crawford (Crawford, Cohen, & Atanacio, 2018) used the back trajectory method to track the contribution of coal-fired power stations in

NSW to fine particle air pollution at Richmond and demonstrated how this changed with the closure of several plants. The closures were Lake Munmorah on the Central Coast in July 2012, Wallerawang near Lithgow in November 2014, and the small Redbank unit in the Hunter Valley in October 2014. Out of 1,420 days for which back trajectories were calculated, 800 days had at least one of the 24 trajectories that crossed a power station, and 620 days showed no crossings. Of the 800 such days, 50% were from the Central Coast, 34% were from Lithgow, and 16% were from the Hunter Valley. The Central Coast was the dominant source of these trajectories in every season except winter, when Lithgow was the dominant source.

On days when the Central Coast was the only likely source of secondary sulfate and industry aged salt, the mass concentrations of these fingerprints were 1.6 $\mu g/m^3$ and 1.4 $\mu g/m^3$ respectively in the later period after the closure of the Lake Munmorah power station, when only Eraring and Vales Point were generating.

On days when Mount Piper near Lithgow was the only likely source of secondary sulfate and industry aged salt the mass concentrations of these fingerprints were 1.1 $\mu g/m^3$ and 0.6 $\mu g/m^3$ in 2015 and 2016 after Wallerawang had closed.

On days when the Hunter Valley was the only likely source of secondary sulfate and industry aged salt the mass concentrations were 1.8 $\mu g/m^3$ and 0.9 $\mu g/m^3$ in 2015 and 2016 after Redbank had closed, leaving Liddell and Bayswater.

It can be seen that the Central Coast is the most frequent source of the particles, and also accounts for the greatest mass concentrations.

Further details of the methods used to estimate the health burden from each plant are in Appendix 1.

Table 14: Health burden attributable to individual power stations, numbers affected per year

Power station	Mortality	Years of Life Lost	Low birth weight	Diabetes
Bayswater	40	376	34	50
Liddell	27	250	22	34
Eraring	87	815	76	113
Vales Point	46	427	40	59
Mount Piper	36	340	35	47

Note: This table includes only Sydney, Central Coast and Hunter regions, excluding the remainder region.

Whichever health impact is considered, Eraring and Vales Point make the largest contribution to the health burden from power generation, since prevailing weather patterns are most likely to carry pollutants from these sources into the Sydney basin where the largest population resides. The continued operation of all the coal-fired generators in NSW imposes a substantial health burden that could be alleviated by imposing stricter licensing conditions for operation that would require post-combustion capture of SO_2 and NO_X or by bringing forward closure of plants where this is uneconomic.

Health impacts from power stations over their remaining operational life

As the existing fleet of NSW generators are old and have limited remaining operational life it is possible to compare health burdens over their projected remaining operations.

Table 15: Remaining operational life based on published or expected closure dates

Station	Planned closure year	Remaining operational life (years)	Number of expected deaths	Number of expected low birth weight babies	Number of expected new onset diabetes
Bayswater	2035	17	685	571	857
Liddell	2022	4	107	89	134
Eraring	2032	14	1,219	1,058	1,579
Vales Point	2030	12	547	475	709
Mount Piper	2042	24	871	835	1,133
Total			**3,429**	**3,029**	**4,412**

*Based on midpoint estimates for Years of Life Lost, low birth weight and diabetes. Excludes the remainder region.

Liddell is scheduled to close in 2022, but suggestions have been made to extend its operational life by five years. If current generation rates are maintained for a further five years this would lead to 1,251 lost years of life, 112 extra babies born below 2,500 g, and 168 extra new diagnoses of diabetes. This estimate ignores the effect of population change over this time and does not account for projected growth in the number of people living in the Hunter region.

Assumptions and uncertainties

These estimates are based on the best available published data, but have required certain assumptions that may prove to be inaccurate. The most important assumptions are:

- That the contribution from coal combustion to fine particle air pollution observed at Richmond applies to the whole of Sydney. This seems reasonable since the distance from the sources to the receiver is large compared to the size of Sydney.
- For the Central Coast and Hunter regions, that the contribution from each power station to ambient fine particles is in proportion to the SO_2 release reported to the National Pollutant Inventory. This assumes random mixing and is not based on wind directions. SO_2 is the primary contributor to secondary particle formation. Until this question has been addressed by atmospheric dispersion modelling using a method such as CALPUFF this is the best available information. For example this

assumption ignores NOx emissions, so Eraring's contribution may be lower since the introduction of low NOx burners in 2011. On the other hand the capacity factor is increasing as the plant is being run at higher output.

- That releases reported to the NPI are accurate.
- That the toxicity of $PM_{2.5}$ in NSW is the same as that observed in North America where the risk estimate for mortality was derived. Suggesting otherwise is like claiming that cigarettes do not cause lung cancer in Australia because there has never been an Australian study of this question.
- That the proportion of back trajectories reported by Crawford 2018 to cross a power station location, multiplied by the average observed concentration represents the proportion of that power station's contribution to annual coal-derived fine particles at Richmond.
- That measurements derived from the two methods used for $PM_{2.5}$ (BAM Beta Attenuation Monitor, and HVS High Volume Sampler) give equivalent results. Differences in results between BAM and a reference high-volume filter method are very small. An older device, Tapered Element Oscillating Microbalance (TEOM), sometimes gives low results (Chung et al., 2011), however TEOM devices are no longer used for $PM_{2.5}$ in NSW.

Conclusion

There is a substantial health burden including deaths, new cases of diabetes, and babies born with low birth weight due to the fine particle air pollution arising from burning coal for electricity generation in NSW. The best estimate of the annual burden is 279 premature deaths, 361 people who develop diabetes, and 233 underweight babies. Because each of the deaths would have multiple contributing factors, it might be easier to think of this as a 10% contribution to 2,790 deaths or a 1% contribution to 27,900 deaths. For mortality and diabetes the timing of these effects is unclear. People dying this year will have been affected by air quality over many years, so removing the air pollution would result in a gradual rather than immediate improvement in health. The impact on birth weights, however, is during pregnancy, especially the last months, so cleaner air after a plant ceases to pollute would result in healthier babies within a few months.

This health burden occurs despite the fact that the power stations are located well outside the major cities, at a distance that was thought to provide adequate separation between the smoke stacks and large numbers of people.

Exposure to fine particle air pollution causes other diseases that are not included in this analysis. This report examines only a selection of diseases for which there is consistent high-quality evidence but has not addressed lung cancer, asthma and chronic lung disease, or non-fatal heart attacks.

While there is residual uncertainty about the exact scale of the health burden, in the health sector we often have to take action with imperfect information. A sick patient is recognised to need hospital treatment before we have an exact diagnosis. Quarantine measures are put in place before a new disease has been fully characterised. The number of people affected by power station air pollution may be some degree greater or less than estimated here, but the burden will keep occurring each year until something is done about it.

Technological solutions exist that can capture and remove SO_2 and NO_2 from combustion gases and these are required on power stations in most developed countries. There will be an important health dividend as ageing coal-fired generators inevitably retire from service, and the health burden is a reason to bring forward retirements or require the installation of modern pollution controls on continuing plants.

Recommendations

1. Power stations should be required to install modern pollution control technology that greatly reduces emissions of SO_2 and NOx.
2. The licences for Australian coal-fired power stations should be amended to set stack emission limits consistent with international best practice.
3. Australia's coal-fired power stations should be required to conduct continuous stack monitoring for SO_2, NOx, particles and mercury, and this data should be made public in real time and as searchable retrospective data.
4. Further research should be commissioned to clarify areas of remaining uncertainty. This would include using detailed atmospheric dispersion modelling to estimate spatial variability of ground level air pollution across the populated areas of NSW, and extension of health analysis to include lung cancer and non-fatal heart attacks.
5. Publicly available ambient air quality monitoring should be conducted at Lithgow and Wyee, which are communities with power stations but no current air monitoring.
6. Data quality assurance should be implemented for the National Pollutant Inventory.
7. The health impacts of electricity generation in other Australian states should be investigated.

Glossary

Term/acronym	Definition
Ambient air	Air at ground level where people breathe. Generally measured at sites away from any point source of pollution.
AusDiab	A large Australian cohort study examining the causes of diabetes.
CALPUFF	CALPUFF is a multi-layer, multi-species non-steady-state puff dispersion model which simulates the effects of time- and space-varying meteorological conditions on pollution transport, transformation, and removal.
Cohort	A research design in which a group of people are followed forwards in time to see what happens to their health.
Confidence interval 95% confidence interval (95%ci)	95% confidence interval or 95%ci is a concise way to indicate the certainty of an estimate. A Hazard Ratio of 1.2 (95% ci 1.1, 1.3) means that the best estimate of the HR is 1.2, and based on the size of the sample it was derived from we can be 95% certain that the true value lies in the range 1.1 to 1.3. The 95% ci of a hazard ratio, relative risk or odds ratio can be carried through to a 95% ci of a disease estimate.
C-R function	The Concentration-Response function is derived from the original epidemiology that proved that fine particle pollution causes these health problems. The C-R function captures how much health problem there is from each unit of exposure.
ESCAPE	European Study of Cohorts for Air Pollution Effects: A large multi-country collaborative European research group.
Hazard Ratio (HR)	See measures of risk.
Incidence	Not to be confused with prevalence. Incidence is the number of new cases of disease in a population over a time period.
LBW	Low Birth Weight, which is sometimes associated with prematurity, but in this analysis defined as low birth weight at full term, i.e. greater than 37 weeks gestation.
Measures of risk	The three common measures of risk are Relative Risk (RR), Hazards Ratio (HR) and Odds Ratio (OR). They are derived from different kinds of analysis but mean more or less the same thing. Relative risk of 1.5 means the incidence of an outcome is 1.5 times higher per year in an exposed group than in an unexposed group. Measures of risk can be expressed per unit of exposure.
Meta-analysis	A method of combining the results from multiple studies into one summary result. It can give greater precision than is available from each single study.
NPI	National Pollution Inventory. An online database of emissions from industrial sites, maintained by the Australian government.
Odds Ratio (OR)	See measures of risk.
Particle characterisation	Chemical analysis or sometimes microscopy to determine the composition of particles which may indicate the source.
$PM_{2.5}$	The size fraction of particles in the air that will pass through a 2.5 micron filter. These are the smallest particles that are routinely measured. $PM_{2.5}$ is a size class, so may vary in composition between locations or even between seasons. Gram for gram it is more damaging to health than the larger particles.
Prevalence	The number of cases of disease in a population at one point in time.
Population weighted average exposure	To describe the average exposure of a population it is incorrect to simply take the average results of all the available monitors, because some monitors represent a large number of residents and others have few surrounding residents. To overcome this the air value for each area is weighted by the population of the area.
Relative Risk (RR)	See measures of risk.
Years of Life Lost (YLL)	A death at a younger age results in greater loss of potential life than a death at an older age, so for some purposes YLL is a better metric than mortality.

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Appendix 1

Attributing health burdens to individual power stations

The extent to which pollution emitted from a power station ends up in ambient ground level air at a distant location can be studied in two ways, either followed forwards with dispersion modelling, or backwards with a back trajectory method. Both of these methods require complex computer modelling of the atmosphere. The formation of secondary sulfate particles is temperature dependent and is greater in summer. The predominant wind pattern in summer is north easterly, the direction that carries air from the Central Coast towards Sydney, so pollution from those sources is frequently picked up at Richmond at high levels.

Attributing health impacts to individual power stations is possible since the publication in 2018 of analysis in which Crawford (Crawford, Cohen et al. 2018) used the back trajectory method to track the contribution of coal-fired power stations in NSW to fine particle air pollution at Richmond and how this changed with the closure of several plants. The closures were Lake Munmorah on the Central Coast in July 2012, Wallerawang near Lithgow in November 2014 and the small Redbank unit in the Hunter Valley in October 2014. Out of 1420 days for which back trajectories were calculated, 800 days had at least one of the 24 trajectories that crossed a power station, and 620 days showed no crossings. Of the 800 such days, 50% were from the Central Coast, 34% were from Lithgow, and 16% were from the Hunter Valley. The Central Coast was the dominant source of these trajectories in every season except winter when Lithgow was the dominant source.

On days when the Central Coast was the only likely source of secondary sulfate and industry aged salt the mass of these fingerprints were 1.6 μg and 1.4 μg respectively in the later period after the closure of the Lake Munmorah power station, when only Eraring and Vales Point were generating.

On days when Mount Piper near Lithgow was the only likely source of secondary sulfate and industry aged salt the mass concentrations of these fingerprints were 1.1 $\mu g/m^3$ and 0.6 $\mu g/m^3$ in 2015 and 2016 after Wallerawang had closed.

On days when the Hunter Valley was the only likely source of secondary sulfate and industry aged salt the mass concentrations were 1.8 $\mu g/m^3$ and 0.9 $\mu g/m^3$ in 2015 and 2016 after Redbank had closed, leaving Liddell and Bayswater.

It can be seen that the Central Coast is the most frequent source of the particles, and also accounts for the greatest mass concentrations.

Table 16: Applying the results from Crawford to the electricity sector contribution to $PM_{2.5}$ in Sydney

	Average 2nd S µg/m³*	Average Ind-Saged µg/m³*	% of all trajectories*	2ndS µg.days	Ind-Saged µg.days	2nd S proportion CFPS	Ind-Saged proportion CFPS
Hunter	1.8	0.9	16	0.288	0.144	0.19699	0.13741
Lithgow	1.1	0.6	34	0.374	0.204	0.25581	0.19466
Central Coast	1.6	1.4	50	0.8	0.7	0.54720	0.66794

Abbreviations: Secondary sulfate (2nd S); Industry aged salt (Ind-Saged); Coal-fired power station (CFPS)

*Data from Crawford (2018)

From the previous work of Cohen (Cohen, Crawford et al. 2012) we know that the mid-point estimate of the total proportion of $PM_{2.5}$ at Richmond that is 2nd S from power stations is 11%, and for ind-Saged is 5.00%. Applying the proportions from Table 16 gives the Hunter power stations as the source of 2.85% of total $PM_{2.5}$ at Richmond, the Lithgow power station as the source of 3.79% of total $PM_{2.5}$ at Richmond, and the Central Coast power stations as the source of 9.36% of the $PM_{2.5}$ at Richmond.

Table 17: Deriving the proportions of $PM_{2.5}$ at Richmond attributable to each cluster

	2nd S proportion CFPS	Ind-Saged proportion CFPS	2nd S CFPS proportion of total $PM_{2.5}$	Ind-Saged CFPS proportion of total $PM_{2.5}$	Proportion of total $PM_{2.5}$ per cluster	% of CFPS burden per cluster
Hunter	0.19699	0.13741	0.02167	0.00687	0.02854	17.84
Lithgow	0.25581	0.19466	0.02814	0.00973	0.03787	23.67
Central Coast	0.54720	0.66794	0.06019	0.03340	0.09359	58.49

Abbreviations: Secondary sulfate (2nd S); Industrial aged salt (Ind-Saged); Coal-fired power station (CFPS)

These results are regarded as indicative as they are based on only the days when the back trajectory intersected only one power station. There were an unknown extra number of days when back trajectories intersected multiple power stations. This does not change the total exposure but may alter the relative contributions.

Within clusters the contribution to the two fingerprints can be assumed to be in proportion to the NPI declared releases of SO_2.

Table 18: Regional proportion of SO_2 emissions by power station

Cluster	NPI SO_2 (tonnes) and proportion of cluster total	NPI SO_2 (tonnes) and proportion of cluster total
Hunter cluster	Liddell 33,490 (40%)	Bayswater SO_2-NPI 50,271 (60%)
Lithgow	Mt Piper 32,000 (100%)	
Central Coast cluster	Eraring 30,533 (65.6%)	Vales Point 16,000 (34.4%)

Taking Eraring as an example, NPI data shows that it releases 65.6% of the SO_2 from the Central Coast cluster. That cluster accounts for 50% of days when a power station is contributing to particles at Richmond, and when it does, secondary sulfate averages 1.6 $\mu g/m^3$ and industrial aged salt averages 1.4 $\mu g/m^3$. This multiplies to a weighted average proportion of the coal-fired power contribution to the fine particles at Richmond of 38.4%.

Appendix 2

Regional health burdens attributable to individual power stations

Estimating individual power station contributions to regional health burdens requires the following assumptions: The Sydney estimates are based on Crawford 2018, the others on NPI data for release of SO_2. The Central Coast particles arise from Central Coast power stations only. The Upper Hunter particles arise from Upper Hunter power stations only. Lower Hunter particles are from both Upper Hunter and Central Coast in proportion to NPI emissions. Mount Piper emissions are an insignificant contributor except for Sydney. Westerly and Southerly winds are both common in the Lower Hunter as supported by the wind roses in figure 4. These winds carry pollution to the Lower Hunter from the Upper Hunter and Central Coast respectively.

Table 19: Percentage of regional health burden attributable to each power station

Power station	Sydney (%)	Central Coast (%)	Lower Hunter (%)	Upper Hunter (%)
Bayswater	10.7	0	38.6	60
Liddell	7.1	0	25.7	40
Eraring	38.4	65.6	23.4	0
Vales Point	20.1	34.4	12.3	0
Mount Piper	23.7	0	0	0

Figure 5: Annual wind roses for Lower Hunter (Williamstown) 9am (left) and 3pm (right) showing frequent winds from the North West (Bayswater, Liddell) and South/SouthEast (Eraring, Vales Point)

Applying this analysis of $PM_{2.5}$ sources to the previously estimated health burdens gives the following tables.

Table 20: Mortality, annual deaths

Power station	Sydney	Central Coast	Lower Hunter	Upper Hunter	Total
Bayswater	16	0	20	4	**40**
Liddell	11	0	13	3	**27**
Eraring	59	16	12	0	**87**
Vales Point	31	9	6	0	**46**
Mount Piper	36	0	0	0	**36**

Table 21: Mortality, Years of Life Lost

Power station	Sydney	Central Coast	Lower Hunter	Upper Hunter	Total
Bayswater	153	0	184	39	**376**
Liddell	102	0	123	26	**250**
Eraring	550	153	112	0	**815**
Vales Point	288	80	59	0.0	**427**
Mount Piper	340	0	0	0	**340**

Table 22: Low Birth Weight, annual number of babies

Power station	Sydney	Central Coast	Lower Hunter	Upper Hunter	Total
Bayswater	16	0	14	4	**34**
Liddell	10	0	10	2	**22**
Eraring	56	10	9	0	**75**
Vales Point	30	6	4	0	**40**
Mount Piper	35	0	0	0	**35**

Table 23: Diabetes, annual number of new cases

Power station	Sydney	Central Coast	Lower Hunter	Upper Hunter	Total
Bayswater	21	0	24	5	**50**
Liddell	14	0	16	3	**33**
Eraring	76	22	15	0	**113**
Vales Point	40	11	8	0	**59**
Mount Piper	47	0	0	0	**47**

Tables 20 to 23 do not include a health burden in the remainder region as there is insufficient information about these areas. This does not suggest that there is no burden, but that it is currently unknown.

Whichever health impact is considered, Eraring and Vales Point make the largest contribution to the health burden from power generation, since prevailing weather patterns are most likely to carry pollutants from these sources into the Sydney basin where the largest population resides. The continued operation of all the coal-fired generators in NSW imposes a substantial health burden that could be alleviated by imposing stricter licensing conditions for operation that would require post-combustion capture of SO_2 and NO_2, or by bringing forward closure of plants where this is uneconomic.

Appendix 3

Allocation of Local Government Areas to regions for analysis

Central Coast	**Sydney**
Central Coast	Bayside
	Blacktown
Lower Hunter	Burwood
Cessnock	Camden
Lake Macquarie	Campbelltown
Maitland	Canada Bay
Newcastle	Canterbury-Bankstown
Port Stephens	Cumberland
	Fairfield
Remainder	Georges River
Bathurst Regional	Hawkesbury
Blayney	Hornsby
Blue Mountains	Hunters Hill
Cabonne	Inner West
Cowra	Ku-Ring-Gai
Dubbo Regional	Lane Cove
Forbes	Liverpool
Goulburn Mulwaree	Mosman
Gunnedah	North Sydney
Hilltops	Northern Beaches
Kiama	Parramatta
Lithgow	Penrith
Liverpool Plains	Randwick
Mid-Coast	Ryde
Mid-Western Regional	Strathfield
Oberon	Sutherland Shire
Orange	Sydney
Parkes	The Hills Shire
Queanbeyan-Palerang Regional	Waverley
Shellharbour	Willoughby
Shoalhaven	Woollahra
Tamworth Regional	
Upper Lachlan Shire	**Upper Hunter**
Uralla	Dungog
Walcha	Muswellbrook
Weddin	Singleton
Wingecarribee	Upper Hunter Shire
Wollondilly	
Wollongong	
Yass Valley	

The other 57 LGAs of NSW were not considered.