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Taiwan's Electronics Industry and Coal Fired Power Plant

Air Quality and Health Impact Assessment

Executive summary

This report investigates the contribution to air pollution in Taiwan of the electronics industry as a result of energy generation through coal fired power plants. Air pollutants emitted by coal burning for electricity generation result in negative impacts on the health of the local population, which also creates a financial burden through increased health care costs. The report provides a detailed analysis of the air quality, health and economic impacts of four existing coal power plants in Taiwan, combining detailed atmospheric modeling with existing epidemiological data and literature. The results of the modelling highlight the health impact directly associated with energy demand from Taiwan's electronics industry.

The modelling used in this report quantifies the health impact associated with power plants which supply the Taiwanese electronics industry. Simulations are performed for scenarios which determine the total health impact in 2016 and the reduction that might be achieved if the electronics industry was to switch to renewable energy, thereby reducing the demand on coal power for electricity generation.

As a result of the emissions from the four coal plants modelled, 88,000 people in Taiwan are exposed to exceedances of WHO air quality guidelines. As a consequence of this additional air pollution, the number of premature deaths in Taiwan is predicted to be between 9,660 and 34,590 over an estimated 30 year plant lifespan.

If the electricity used by the Taiwanese electronic industry was generated with renewable energy, operations at coal fired power stations could be reduced. In this scenario we calculate that the number of premature deaths in Taiwan would be between 8,250 and 29,430 over an estimated 30 years plant lifespan. This represents a reduction of 14.8% (central estimate) or a saving of 100 lives per year. If the TSMC company alone were to use renewable energy the number of premature deaths in Taiwan would be between 9,240 and 33,000.

The report also shows that these health impacts cost Taiwan 61,492 Million NTD per year. Should the Taiwanese electronic industry switch to renewable power 9,134 Million NTD could be saved annually, while if only TSMC were to use renewable power, the saving would be 2,814 Million NTD per year.

The Taiwanese electronics industry and Taiwanese government must shift to renewable energy if they want to prevent the emission of harmful pollutants, and protect the health of their citizens.

Introduction

Air pollution is responsible for many negative health impacts and is estimated to cause over 7 million premature deaths across the world annually,[1] costing the world's economy nearly 225 billion USD.[2] Whilst air pollutants arise from a diversity of sources, fossil fuel burning is a principal contributor and burning coal for power generation is one of the globes major sources of air pollution[3].

Emissions from coal fired power plants (CFPPs) elevate the levels of particulate matter and gaseous pollutants in the air over a large area, spanning hundreds of kilometers. In the case of Taiwan this impedes the ability of cities across the island to meet their public health standards.

This pollution increases the risk of diseases such as stroke, lung cancer, heart and respiratory diseases in adults, as well as respiratory infections in children.[4] These effects lead to premature deaths in the affected populations. In addition, emissions from coal plants cause acid rain, which can affect forests, crops and soils, as well as fallout of toxic heavy metals such as arsenic, nickel, chrome, lead and mercury.

Greenhouse gas emissions from CFPPs must be reduced to limit anthropogenic global warming.[5] OECD[6] countries need to phase out coal by 2030, and the rest of the world by 2050 to prevent disastrous climate change.[7] Many nations are working to phase-out coal in order to meet their commitments under the 2016 Paris agreement[7] to keep global temperature rise below 1.5°C.

Modelling emissions, health and economic impacts

In order to quantitatively assess the impacts of Taiwan's electronics industry on air quality, and the resulting impacts to human health, we modelled the dispersion of air pollutants emitted by four CFPPs across Taiwan. Details of the power plants modelled and the scenarios tested are shown in Table 1.

To allow us to quantify the impact of the power plants, and the potential reduction should the electronics industry switch to renewable sources of electricity, the model was run three times for three

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[1]https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action
[2] http://www.worldbank.org/en/news/press-release/2016/09/08/air-pollution-deaths-cost-global-economy-225-billion
[3] Crippa M, Guizzardi D, Muntean M, Schaaf E, Dentener F, van Aardenne JA, Monni S, Doering U, Olivier JG, Pagliari V, Janssens-Maenhout G. (2018). Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4. 3.2. Earth System Science Data. 10(4):1987-2013.
[4] WHO Ambient Air Pollution database, Global Burden of Disease study
[5] IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
[6] Organisation for Economic Co-operation and Development
[7] Paris Agreement. United Nations Treaty Collection. 8 July 2016. Archived from the original on 21 August 2016 https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

different scenarios:

- **Baseline:** Actual emissions
- **Scenario 1:** Reduced emissions. The electronics industry switches to renewable electricity reducing demand at CFPPs
- **Scenario 2:** Reduced emissions: TSMC switches to renewable electricity reducing demand at CFPPs.

Scenario 1 and 2 were derived by comparing the electricity generated by each section of the Taiwan national power grid in 2016 with the demand of the EM industry in that section. The reduction in demand in each section of the grid was then calculated and the ratio of the 2016 demand and estimated reduced demand was used to calculate a scaling factor for each of the modelled CFPPs. This scaling factor was applied to determine possible emissions rates should the EM industry stop drawing power from Taiwan's CFPPs. Detail description of the scenario settings and scaling factor listed in Appendix 1.

Each model simulation predicts pollutant concentrations resulting from the CFPPs for the specified emission regime over the course of one calendar year. The specific year modelled is 2016, which represents the most recent year with available input data for modelling. Input data describing the emissions are extracted from the Environmental Impacts Assessments (EIAs) for each plant.[8] A detailed technical description is provided in Appendix 2. The methodology used in the Health Impact Assessment and Economic Cost Calculation are also provided in the appendix.

National Power Grid Area	Plant Name	Baseline	2016 Generation (GWh)	Scenario 1 Effective Generation (All EMs)	Scenario 2 Effective Generation (TSMC)	Scenario 1 Adjustment (All EMs)	Scenario 2 Adjustment (TSMC)
Middle	Taichung	100%	42,104.02	35,323.51	40,090.83	84%	95%
Middle	Mailiao (IPP)	100%	13,402.80	11,142.63	12,865.19	83%	96%
South	Xinda	100%	15,774.76	12,761.20	14,358.54	81%	91%
East	Hoping[9]	100%	8,814.10	8,814.10	8,814.10	100%	100%

Table 1. Modelled Power Plants and Scenarios

[8] 台灣電力公司107年統計年報 https://www.taipower.com.tw/upload/_userfilesfiles/107%E5%B9%B4%E5%B9%B4%E5%A0%B1.pdf (Taipower 2018 Statistic Annual report)

[9] http://www.hppc.com.tw/Power%20Plant%20Introduction/Report/106%E5%B9%B4%E7%99%BC%E9%9B%BB%E6%A5%AD%E5%B9%B4%E5%A0%B1.pdf

Results

Health Impact

We find that emissions from the modelled CFPPs has the potential to cause between 322 and 1,153 premature deaths in 2016, with a central estimate of 674 cases (Figure 2). If the Taiwanese electronics industry used renewable electricity, reducing the demand on Taiwan's CFPP fleet, 100 annual premature deaths are likely to be avoided, totalling 3,000 lives over an estimated 30 year plant operation time (Figure 2).

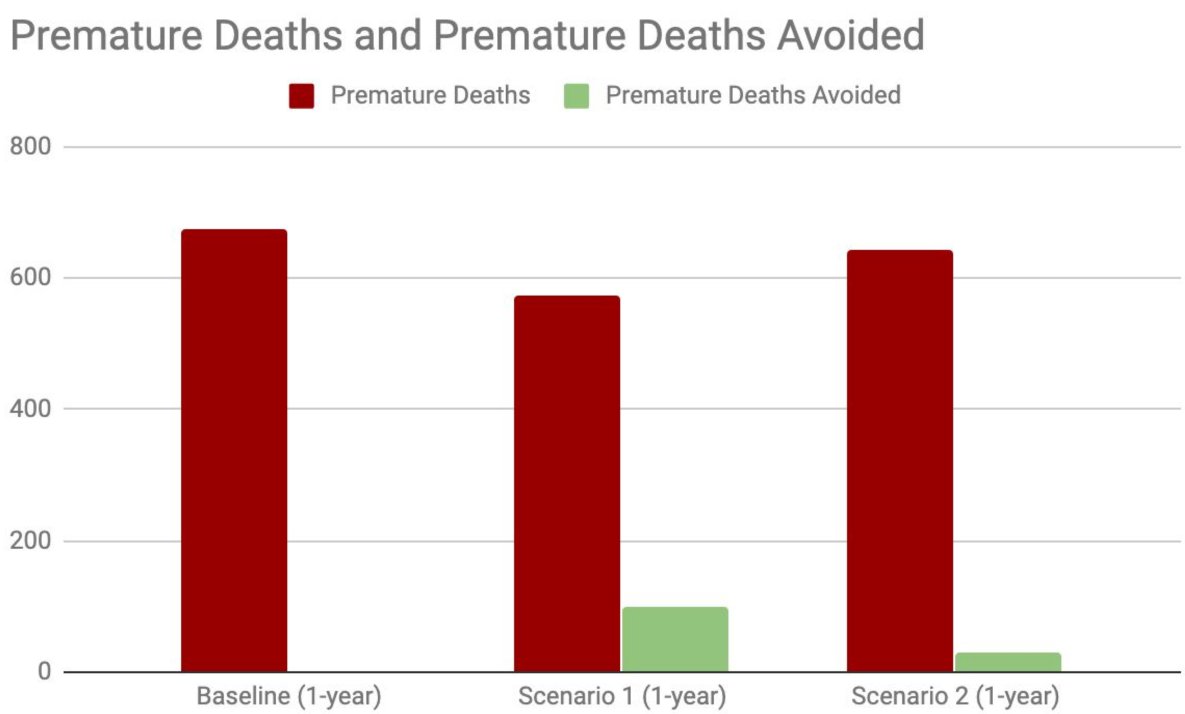

Figure 1. Modelled number of premature deaths annually due to the modelled Coal Fired Power Plants for Baseline, Scenario 1 and Scenario 2. Shown are central estimates, the upper and lower range of values printed in Table 3.

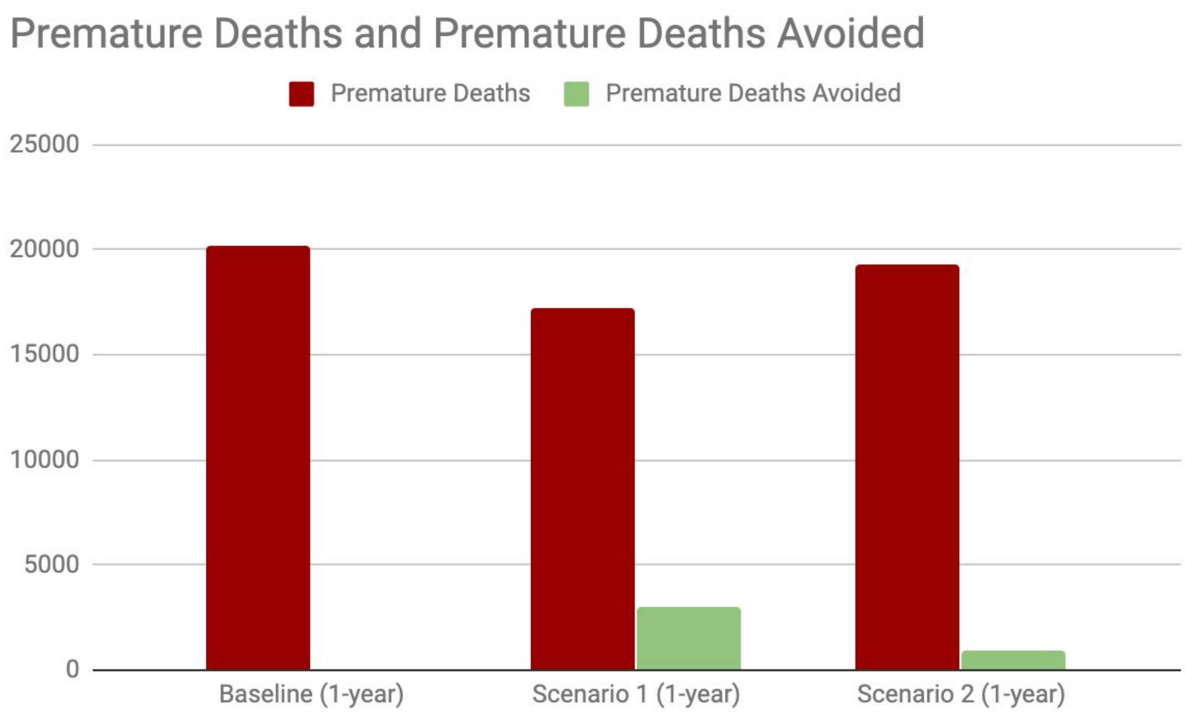

Figure 2. Central estimates of the total premature deaths for 30 years lifespan due to the modelled power plants for Baseline, Scenario 1 and Scenario 2. The Differences represents the premature deaths that can be prevented if electricity demand from the electronics industry is diverted to renewable sources.

Pollutant concentration

Figures 3 to 5 show the projected annual average NO_2, $PM_{2.5}$ and SO_2 pollution from the modelled power plants under Baseline. During unfavourable meteorological conditions, or when plant emissions are worst, higher pollutant concentrations are attained for short time periods. The maximum 24-hour mean SO_2 and $PM_{2.5}$ pollution and the maximum 1-hour mean concentration for NO_2 and SO_2 are also shown in figures 3 to 5. Spatial comparisons between the Baseline and scenarios 1 and 2 are shown in Appendix 3.

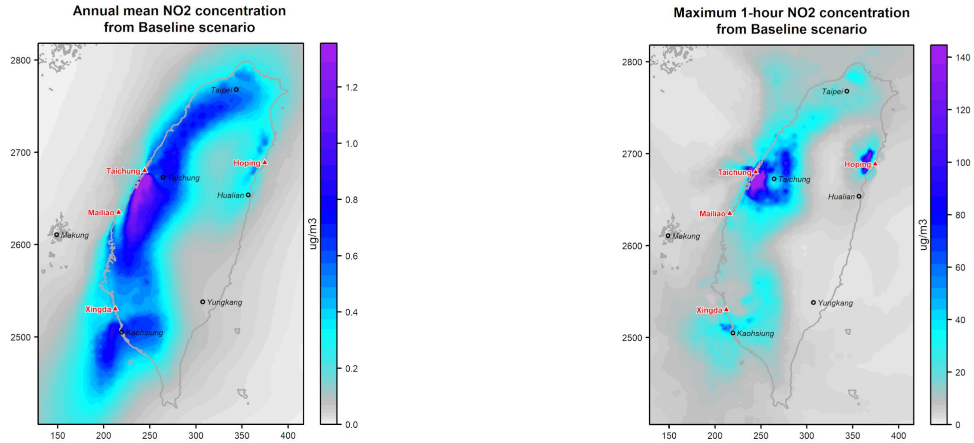

Figure 3. Baseline Scenario annual mean (left) and 1-hour mean (right) contribution to surface NO_2 concentration across Taiwan. The studied plants are marked as a red triangle.

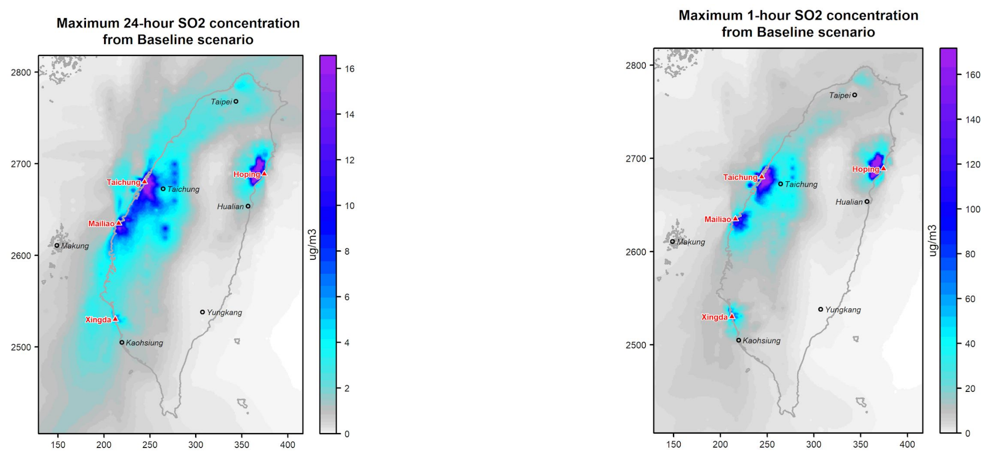

Figure 4. Maximum 24-hour mean (left) and 1-hour mean (right) contribution to surface SO_2 concentration across Taiwan. The studied plants are marked as a red triangle.

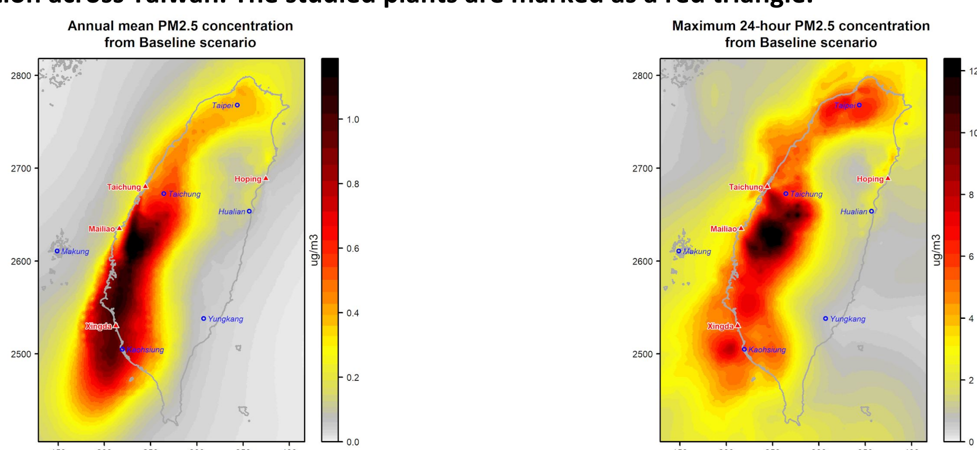

Figure 5. Annual mean (left) and 24-hour mean (right) contribution to surface $PM_{2.5}$ concentration across Taiwan. The studied plants are marked as a black-red triangle.

The maximum contribution to ground level pollutant concentrations is shown in Table 2. Modelling of Baseline and Scenario 2 emissions found that one of the six WHO air pollution guidelines are violated in inhabited areas (Table 2). Under Scenario 1 none of the WHO guidelines are exceeded by power plant emissions.

Under the Baseline and Scenario 2 projections, a total of 88,625 people are exposed to 1-hour NO_2 levels exceeding WHO guidelines. However, should all of the electronics industry switch to renewable power (Scenario 1), exceedances of the WHO 1-hour NO_2 guideline may be avoided when considering the modeled CFPP emissions alone.

In the case of $PM_{2.5}$ and SO_2 the power plant contribution to short-term and annual mean pollution levels is not sufficient on its own to exceed the WHO guidelines, however this study does not account for any other source of air pollution and so exceedances cannot be ruled out.

	NO_2 (μg/m³)		SO_2 (μg/m³)		$PM_{2.5}$ (μg/m³)	
	Annual	1h	24h	10min[10]	Annual	24h
Air Quality Guideline	**40.0**	**200**	**20.0**	**500**	**10.0**	**25.0**
Baseline	1.8	228.4	16.9	202.6	1.3	12.9
Scenario 1	1.5	190.5	14.1	169.3	1.1	11.0
Scenario 2	1.7	217.2	16.0	192.7	1.2	12.4

In these calculations, we only consider the contribution to the total air pollutant burden from the power plant itself. No consideration is given to pollution from other sources and so total concentrations are underestimated. It is likely that the actual number of people exposed to dangerous pollution levels is even higher.

Impact on Human Health

Exposure to the air pollutants modelled in this study, especially at concentrations exceeding the WHO guidelines, carries a substantial risk of developing or exacerbating respiratory and other diseases, especially for vulnerable groups such as children and elderly people. Applying a widely used health

[10] Model values for 10-minute intervals are lower limits. The reason for this is that we have not actually computed 10-minute average concentrations, but only 1-hour average concentrations. These can be used as a lower limit as there must be a 10-minute interval which has at least the same average concentration as the 1-hour interval.

impact assessment method[11,12,13] (see Appendix), we estimated the additional number of annual premature deaths due to the excess pollution from the modelled power plants.

The results are shown in Figure 1 and Table 3. We find that the pollution from the power plants is responsible for 674 (95% confidence interval 322-1,153) additional premature deaths each year. 72% of these fatalities are due to diseases caused by $PM_{2.5}$ pollution.

If the electronics industry switched to renewable sources of electricity the resultant reduction in pollution would reduce the total number of premature deaths by 14.8%, to 574 annually. This reduction would be only 31 if TSCM moved to renewable power alone.

		Baseline (Current Situation)			Scenario 1 (All Electronic Manufacturers)			Scenario 2 (TSMC)		
Pollutant	**Cause**	**Central estimate**	**Low estimate**	**High estimate**	**Central estimate**	**Low estimate**	**High estimate**	**Central estimate**	**Low estimate**	**High estimate**
$PM_{2.5}$	Chronic obstructive pulmonary disease	60	36	86	51	31	73	58	35	82
	Diabetes	63	10	125	53	8	107	60	9	120
	Ischemic heart disease	119	72	170	102	61	145	114	69	162
	Lung cancer	70	28	115	60	24	98	67	27	110
	Lower respiratory infections	0	0	1	0	0	1	0	0	1
	Stroke	102	61	145	87	52	123	97	58	138
	Other cardiovascular diseases	64	39	92	55	33	78	62	37	88
	Other respiratory	9	5	12	7	4	10	8	5	12

[11] Anenberg, SC, Horowitz, LW, Tong, DQ and West, JJ. 2010. *An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling*. Environmental health perspectives. DOI:10.1289/ehp.0901220.
[12] Koplitz, SN, Jacob, DJ, Sulprizio, MP, Myllyvirta, L. and Reid, C, 2017. *Burden of disease from rising coal-fired power plant emissions in Southeast Asia*. Environmental science & technology. DOI: 10.1021/acs.est.6b03731
[13] Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, Turner MC, Pope CA III, Thurston G, Calle EE, Thun MJ. 2009. *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality.* HEI Research Report 140. Health Effects Institute, Boston, MA. DOI: 10.1021/acs.est.6b03731

	diseases									
	PM2.5 total	487	251	745	416	214	636	466	240	713
NO_2	All causes, NO_2	187	71	408	158	60	345	177	68	387
All	**Total**	**674**	**322**	**1,153**	**574**	**275**	**981**	**643**	**308**	**1,100**

Table 3. Modelled number of annual premature deaths due to excess pollution for Baseline, Scenario 1 and Scenario 2 ("Low" and "High" show the bounds of the 95% confidence intervals).

Economic cost of the health impacts

The economic cost of the health impact relating to $PM_{2.5}$ described above have been assessed. An economic valuation of human health impacts represents an estimate of what would be an acceptable cost for avoiding the population level health impact in question. The approach used in this paper measures people's own willingness to pay to avoid a risk of death. This report has shown that a large number of people in Taiwan are exposed to the health impacts of poor air quality.

The approach to this willingness-to-pay study for air pollution followed here is recommended by OECD (2012)[14] and further details are provided in the Appendix 2. The economic costs calculated are summarised in Table 4.

The health cost associated with the baseline scenario is NTDmln 61,492 (NTDmln 14,235 - NTDmln 179,302). If the electronics industry switched to renewable sources of electricity the resultant reduction in health cost would be NTDmln -9,134 (NTDmln -2,108 - NTDmln -26,740) annually. This reduction would be NTDmln -2,814 (NTDmln -646 - NTDmln -8,307)if only TSCM moved to renewable power.

	Central Estimate (NTDmln)	Low Estimate (NTDmln)	High Estimate (NTDmln)
Base Case	61,492	14,235	179,302
Scenario 1	52,358	12,127	152,562
Scenario 2	58,678	13,589	170,995
Scenario 1 Reduction from Base Case	9,134	2,108	26,740
Scenario 2 Reduction from Base Case	2,814	646	8,307

Table 4. Estimated annual cumulative health costs to society caused by modelled power plant emissions (Millions of NTD)

[14] OECD 2012: Mortality Risk Valuation in Environment, Health and Transport Policies. DOI:10.1787/9789264130807-en

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Glossary

air quality guideline	A guideline for the *pollutant concentration*, issued by the WHO. Pollutant concentrations above the guideline value are deemed to be harmful to human health. For levels below guideline concentrations, it is not clear whether, or to what extent, human health is put at risk.
CFPP	*coal-fired power plant*
exceedance	A period of time when the concentration of an air pollutant is greater than the appropriate *air quality guideline*.
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. This implies that 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 *central estimate*. It is somewhere inside the confidence interval. The bounds of the confidence interval are called *low* and *high estimate* Synonyms: 95%-confidence interval (in this work), “between x and y”
central estimate	see *confidence interval*
low estimate	see *confidence interval*
high estimate	see *confidence interval*
CRF	**Concentration Response Factor**
emission rate	The amount of a pollutant that is emitted per unit time by a specific power plant (e. g. 100 kg/hour). In some cases, this is used instead of the *emission concentration* as a measure of how polluting the coal-fired power plant is.
emission limit	The maximum allowed *emission concentration* (or sometimes *emission rate*) for a specific plant. It can be prescribed by national standards, environmental permit conditions (which can be based on national standard but can also be looser or stricter) or some other legal regulation.
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 NO_x group and SO_2. Synonym (here): *pollutant*
pollutant concentration	The actual concentration of some pollutant at any location (close to or far away from a power plant). 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).
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).

	Not to be confused with: *air quality guideline, emission limit*
flue gas	The gas that exits the power plant via its stacks.
NO	**Nitrogen monoxide.** A trace gas that is produced in all combustion processes. It converts from and to NO_2. 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 NO_x group.
NO_x	**Nitrogen oxides.** A generic term for NO and NO_2, a group of trace gases that are harmful to human health.
SO_2	**Sulfur dioxide.** Sulfur dioxide is a trace gas produced by industrial processing of materials that contain sulfur, including coal burning in power plants and processing of some mineral ores. About 99% of the sulfur dioxide in air comes from human sources. 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 (→ $PM_{2.5}$).
dust	**Solid airborne particles.** In CFPP *flue gas*, this is mainly fly ash. A subclass of dust is $PM_{2.5}$.
$PM_{2.5}$	**Fine particulate matter.** Solid particles with aerodynamic diameter of less than 2.5µm (i. e. small dust particles).[15] 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 kilometers. 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 NO_x) which form $PM_{2.5}$ in the atmosphere. $PM_{2.5}$ is harmful to human health and thus an air pollutant.
RR	**Risk Ratio**
µg	**Microgram.** A millionth of a gram. (about the mass of an ant's antennae)
WHO	*World Health Organization*

[15] Definition by the United States Environmental Protection Agency, https://www.epa.gov/pm-pollution/particulate-matter-pm-basics (accessed 11 July 2019)

Appendix 1. Scenario Settings and Scaling Factor

In 2016, there were 4 coal power plants operating in Taiwan national grid, locating separately in the North, Middle, South and East grid area. (See table below). Coal power consumptions in 2016 were provided by these 4 coal power plants.

Grid Name	Cities and Counties	Coal Plants in the grid
North	Taipei, New Taipei, Keelung, Hsinchu, Taoyuan, Yilan	X [16]
Middle	Taichung, Miaoli, Changhua, Nantou, Yunlin	Taichung (550MW*10) Mailiao (600MW*3)(IPP)
South	Kaohsiung, Tainan, Chiayi,Pingtung	Xinda (500MW*2+550MW*2)
East	Hualien, Taitung	Hoping (650MW*2)

Scenario 1 2016 EM Power Consumption: 32,579.29GWh

Grid District	2016 Operating Coal plants	2016 Coal Plant Power Generation (GWh)	Total Power Consumption (GWh)	Coal power consumption (GWh) [17]	Coal Power generation adjustment
North	-	-	55%-> 17918.45	6629.83	-
Middle	Taichung	42,104.02	20%-> 6515.8	2410.85	-6,780.51
	Mailiao	13,402.80			-2,260.17
South	Xinda	15,774.76	25%-> 8144.75	3013.56	-3,013.56
East	-	-	0	-	-
All		71,281.58	32,579.29	12,054.24	-12,054.24

[16] Linkuo coal plant had NOT started to operate until the end of 2016.
[17] Coal power accounts for 37% of the total electricity system

In 2016, the overall power consumption for electronic manufacturing was 32,579.29GWh. According to data from Taipower[18] and BOE[19], 55% of EM power consumption was from northern grid, 20% from middle grid and 25% from southern grid (detailed number listed in the table above).

Since coal power accounts for 37% of the total power system, we multiply the power consumption by 37% to calculate the "coal power consumption" in different districts. However, northern district did not have operating coal plant, we assume the coal power consumption in northern district was also provided by Taichung & Mailiao power plant in the middle district.
Coal power generation adjustment concludes the reduction of each coal plants if the EM did not use coal power as their power source.
(Note: our assumption did not consider cases when power is transferred to other districts)

Scenario 2 TSMC 2016 Total Power Consumption: 9,639.57GWh

	2016 Operating Coal plants	**2016 Plant Power Generation (GWh)**	**TSMC Power Consumption (GWh)**	**TSMC Coal Power Consumption (GWh)**	**Scenario 2 Power generation adjustment (GWh)**
North	-	-	4,328.41	1,601.51	-
Middle	Taichung	42,104.02	1,483.55	548.91	-2,013.19
	Mailiao	13,402.80			-537.61
South	Xinda	15,774.76	3,827.61	1,416.22	-1,416.22
East	-	-	-	-	-
All		71,281.58	9,639.57	3,566.64	-3,566.64

In 2016, the overall power consumption for TSMC was 9,639.57GWh. Following the same setting as scenario 1, TSMC coal power consumption and Coal power generation adjustment show as table above. According to data from Taipower[20] and BOE[21], 55% of EM power consumption was from northern grid, 20% from middle grid and 25% from southern grid (detailed number listed in the table above).

Since coal power accounts for 37% of the total power system, we multiply the power consumption by 37% to calculate the "coal power consumption" in different districts. However, northern district did not have operating coal plant, we assume the coal power consumption in northern district was also provided by Taichung & Mailiao power plant in the middle district.
Coal power generation adjustment concludes the reduction of each coal plants if the EM did not use coal power as their power source.

[18] 台電公司，AMI資料委託技術服務
[19] 經濟部能源局，能源平衡表
https://www.moeaboe.gov.tw/ECW/populace/web_book/WebReports.aspx?book=B_CH&menu_id=145
[20] 台電公司，AMI資料委託技術服務
[21] 經濟部能源局，能源平衡表
https://www.moeaboe.gov.tw/ECW/populace/web_book/WebReports.aspx?book=B_CH&menu_id=145

Appendix 2. Methodology of Health Impacts Modeling

Method overview

The impacts of the coal fired power plant is derived using a combined approach that uses an atmospheric dispersion modeling system to estimate pollutant concentrations and demographic data to estimate health effects. The atmospheric dispersion model consists of two major components:

1. **The pollution model**

In a first step, a numerical weather model is used to simulate the regional meteorological conditions around the power plant. It is combined with a chemistry model to study the propagation of the power plant emissions to its environment.

a) **Meteorology model.** The meteorology around the power plant is modelled using version 3 of the *The Air Pollution Model* (TAPM)[22]. Although TAPM includes the ability to model pollutant dispersion, only the meteorology component of TAPM is used. TAPM is run on two nested domains centred around the power plant. The model domains have spatial resolutions of 40 km and 10 km, respectively, getting finer towards the center (Figure A.1). Boundary conditions are derived from the GASP model of the Australian Bureau of Meteorology. In each TAPM simulation, the model has a nine day spin up period covering the last nine days of 2017. TAPM is then run for the whole year of 2018, to provide data for the analysis.

b) **Atmospheric chemistry-transport model.** The dispersion, chemical transformation and deposition of the power plant emissions of NO_x, SO_2 and primary $PM_{2.5}$ is modelled by the *CALPUFF* model (version 7).[23] As we are solely focusing on the impacts from the power plant, no other emission sources are included in the model. Background concentrations of O_3, NH_3 and H_2O_2 are included for use by the chemistry module.[24] Both emission scenarios (Baseline, Scenario 1, and Scenario 2) are modelled. The model outputs a time series of near-surface concentrations of the pollutants for analysis to gridded receptor locations across the model domains.

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[22] Peter J. Hurley, Mary Edwards, William L. Physick and Ashok K. Luhar: *TAPM V3 – Model Description and Verification*, Clean Air, **39**, 32-36, 2005.

[23] S. Scire, J & G. Strimaitis, D & Yamartino, Robert. (2000). *A user's guide for the CALPUFF dispersion model (version 5)*. http://www.src.com/

[24] Chemical transformation of sulphur and nitrogen species was modeled using the ISORROPIA/RIVAD chemistry module within CALPUFF. The chemical reaction set requires background pollutant concentration parameters (O_3, NH_3 and H_2O_2 levels) which were obtained from Geos-Chem global benchmark simulations (http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_v8-01-04#1-year_benchmarks)

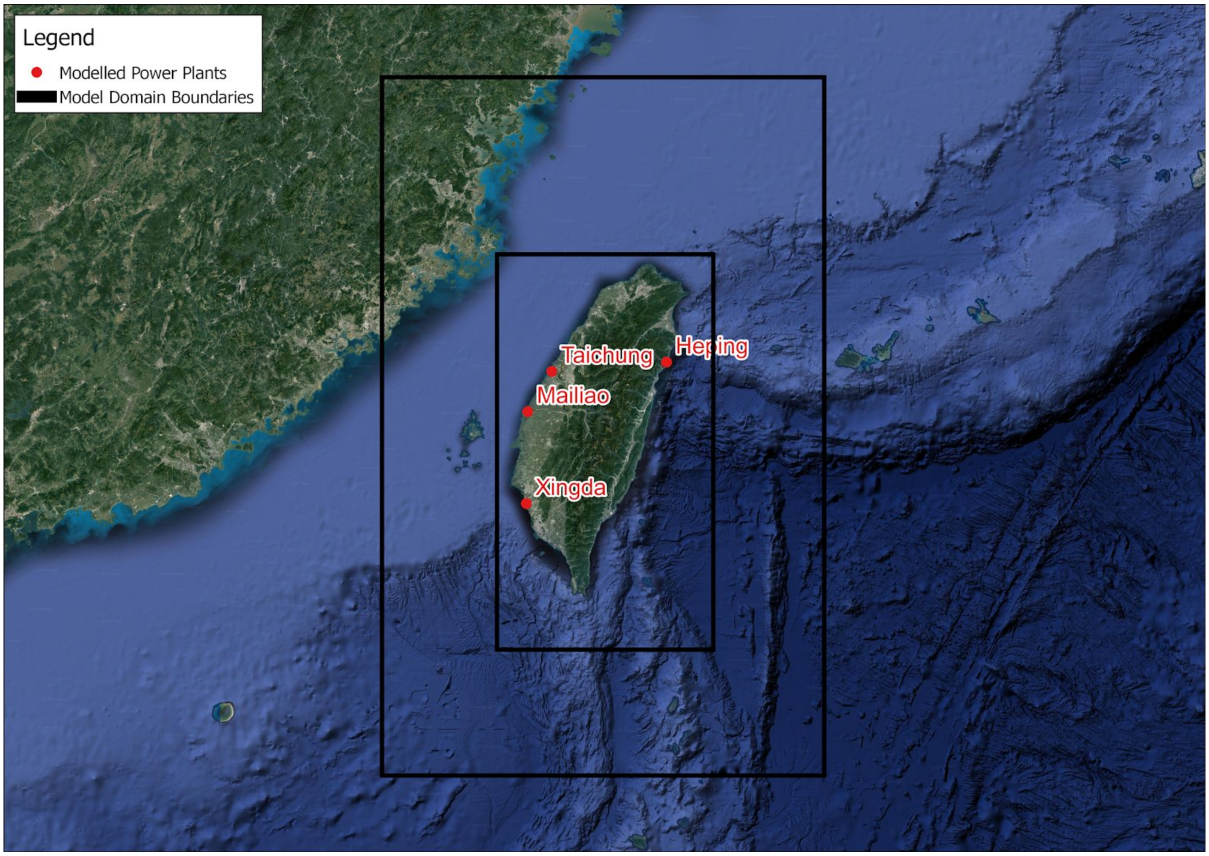

Figure A.1: A numerical weather model with two nested domains (Black boxes) around the modelled sources (Red circles) is run.

Emission data sources

The pollutant emission rates and flue gas release characteristics used for the modeling are based, as far as possible, on data disclosed by project proponents. The following data was collected from Environmental Impact Assessments,Taipower annual report [25], Coal Swarm Global Plant Tracker [26] and Platts world electric power plants database[27]:

- Annual emissions volumes (AEV)
- Emissions rates at full operation (ER)
- Pollutant concentrations in flue gas (CFG)
- Flue gas volume flow (FGV)
- Coal type
- Stack height

[25]Taipower 2018 Annual Report https://www.taipower.com.tw/upload/_userfilesfiles/107%E5%B9%B4%E5%B9%B4%E5%A0%B1.pdf (Taipower 2018 Statistic Annual report)
[26] https://endcoal.org/plant-tracker/
[27] http://www.platts.com/products/world-electric-power-plants-database

- Flue gas release temperature and velocity
- Stack location

The atmospheric model was run for a full calendar year at the full-operation emissions rates, and the resulting ground-level pollutant concentration fields were used as such for assessing maximum short-term air quality impact. For the purposes of health impact assessment, the average concentrations were scaled down by the plant's projected load factor, effectively spreading the plant's annual emissions volume evenly through the year. The stack inner diameter was estimated using the median value for comparable plants.

Table A1. Modelled CFPP geometry

Plant	Units	Latitude	Longitude	Stack height (m)	Stack diameter (m)	Flue Gas Exit Speed (m/s)	Estimated Flue Gas Exit Temperature (°C)
Hoping	1-2	121.76	24.31	250	6.5	20	330
Taichung	1-10	120.48	24.21	250	6.5	20	330
Mailiao MP	1-3	120.21	23.80	250	6.5	20	330
Xingda	1-4	120.20	22.86	250	6.5	20	330

Table A2. Modelled CFPP scenarios

Plant	Capacity MW (electrical)	Scenario 1 Baseline	Scenario 2 Adjustment	Scenario 3 Adjustment
Hoping	2 x 650	100%	84%	95%
Taichung	10 x 550	100%	83%	96%
Mailiao MP	3 x 600	100%	81%	91%
Xingda	2 x 500 + 2 x 550	100%	100%	100%

Table A3. Modelled baseline emission rates in metric tonnes per year per plant unit

Unit	SO_2 (t/a)	NO (t/a)	NO_2 (t/a)	Dust* (t/a)
Hoping 1-2	1350.8	609.4	41.0	168.7
Taichung 1-10	1064.55	2881.4	193.8	265.9
Mailiao MP 1-3	942.1	425.0	28.6	117.6
Xingda 1-2	695.4	1882.1	126.6	173.7

Xingda 3-4	764.9	2070.4	139.2	191.0

*Total particulate matter. This was further separated into particles smaller than 2.5 µm ($PM_{2.5}$) and particles between 2.5 and 10 µm (PM_{10}), based on a typical particle size distribution for plant with Bag House emissions control.

The power plant and emission data shown in Tables 1, 2 and 3 were used as the basis of modeling the plants' air quality impacts using the CALMET-CALPUFF modeling system. The modeling domains used are shown in Figure 1.

To establish short-term maximum air quality impacts, these full-operation emission rates were modeled for a whole calendar year. Annual air quality impacts and health impacts are assessed based on average plant operating load in 2017.

2. Health impact assessment

The results of the pollution model (step 1) are used to assess the number of people exposed to concentrations which violate the WHO guidelines and to estimate the impact of this pollution on the health of the local human population.

a) **Exposure to guideline level exceedances.** Using global population data with 1 km resolution, we assessed the number of people living in areas that exceed WHO guidelines. There are guidelines that refer to average concentration and others that refer to maximum concentrations within a certain time interval. For those referring to average concentrations, we used the temporal mean of the full year of analysis time. For the maximum concentrations, we calculated for each of the chemical model receptors individually the maximum value of the appropriate temporal running mean. The NO_2 concentration dataset of Larkin et al (2017) is used to determine the population exposed to greater than the WHO annual mean guideline[28].

b) **Health impact.** The number of fatalities caused by the excess pollution have been assessed using empirical values of *relative risks* relating various causes of premature deaths to increases in pollutant concentrations. The relative risk *r* expresses how much more likely an individual is to die prematurely if they are exposed to a certain excess pollution than if they were not exposed:

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

where m_x is the mortality (number of deaths per number of inhabitants) under the increased pollution Δx, and m_0 is the mortality in absence of the excess pollution. In state-of-the-art epidemiological models, r depends exponentially on x for $m_x << 1$:[29,30]

[28] Larkin, A., Geddes, J. A., Martin, R. V., Xiao, Q., Liu, Y., Marshall, J. D., ... & Hystad, P. (2017). Global land use regression model for nitrogen dioxide air pollution. *Environmental science & technology*, *51*(12), 6957-6964. 10.1021/acs.est.7b01148

[29] Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, Turner MC, Pope CA III, Thurston G, Calle EE, Thun MJ. 2009. *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality.* HEI Research Report 140. Health Effects Institute, Boston, MA. http://dx.doi.org/10.1021/acs.est.6b03731

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

with c being a constant called *concentration response factor.* Combining Eqs. (1) and (2) gives

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

Since the number of deaths is the population number P times the mortality, the number of people dying under the higher pollutant concentration is

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

The number of deaths attributable to the excess pollution is

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

Values for r in the scientific literature may be broken down to different death causes or be a total for one substance.

Data sources for the health impact assessment

- **Population.** We used the 1km resolution global population data for 2010 from Socioeconomic Data and Applications Center (sedac).[31]
- **Country boundaries** are taken as defined in version 3.6 (May 2018) of the GADM project.[32]
- **Concentration response factors (CRFs).** We used the CRFs listed in Tab. A.1. CRFs have been computed from relative risks given in WHO (2013)[33] for NO_2, Pope et al. (2015)[34] for $PM_{2.5}$-*diabetes* and Krewski et al. (2009)[35] for all other $PM_{2.5}$. The same values are used for all countries.
- **Background mortality** is taken from the IHME Global Burden of Disease Study 2017.[36] The data set provides values per death cause per country. The numbers for the countries and causes in this report are listed in Tab. A.2.

Allocation of death cause names from the CRFs to background death rates is shown in Tab. A.3.

[30] Anenberg SC, Horowitz LW, Tong DQ, West JJ. An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. *Environ Health Perspect*. 2010;118(9):1189–1195. doi:10.1289/ehp.0901220

[31] Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. *Gridded Population of the World, Version 4 (GPWv4): Population Density Adjusted to Match 2015 Revision UN WPP Country Totals, Revision 11.* Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4F47M65. Accessed 15th May 2019.

[32] https://gadm.org

[33] World Health Organization (WHO), 2013. Health risks of air pollution in Europe-HRAPIE project, http://www.euro.who.int/__data/assets/pdf_file/0006/238956/Health_risks_air_pollution_HRAPIE_project.pdf

[34] C. Arden Pope, III, Michelle C. Turner, Richard T. Burnett, Michael Jerrett, Susan M. Gapstur, W. Ryan Diver, Daniel Krewski, and Robert D. Brook, *Relationships Between Fine Particulate Air Pollution, Cardiometabolic Disorders, and Cardiovascular Mortality,* Circulation Research. 2015; **116**:08–115. http://dx.doi.org/10.1161/circresaha.116.305060

[35] Table 11 in: Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, Turner MC, Pope CA III, Thurston G, Calle EE, Thun MJ. 2009. *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality.* HEI Research Report 140. Health Effects Institute, Boston, MA. http://dx.doi.org/10.1021/acs.est.6b03731

[36] GBD 2017 Mortality Collaborators. *Global, regional, and national age-sex-specific mortality and life expectancy, 1950–2017: a systematic analysis for the Global Burden of Disease Study 2017.* The Lancet. 8 Nov 2018;392:1684-735. http://dx.doi.org/10.1016/S0140-6736(18)31891-9.

	NO_2	$PM_{2.5}$
	relative risk at 10 μg m^{-3} increase	relative risk at 10 μg m^{-3} increase
All causes	1.055 (1.021-1.080)	-
Lower respiratory infections	-	1.128 (1.077-1.182)
Lung cancer	-	1.142 (1.057-1.234)
Chronic obstructive pulmonary disease	-	1.13 (1.02-1.26)
Diabetes	-	1.128 (1.077-1.182)
Stroke	-	1.128 (1.077-1.182)
Ischemic heart disease	-	1.128 (1.077-1.182)

Table A.1. Concentration response factors for NO_2 and $PM_{2.5}$ derived from relative risks for a standard increase of 10 μg/m^3. The CRFs have been computed from the relative risks using Eq. (2). Brackets show 95% confidence intervals.

Cause	All	LRI	LC	COPD	Diabetes	Stroke
Death rate per million	5652 (5198-6138)	245 (209-294)	161 (139-186)	412 (366-468)	159 (134-187)	1030 (933-1138)

Table A.2. Background death rates for Bangladesh from the 2017 IHME Global Burden of Disease dataset. Annual deaths per million with 95% confidence ranges. Death causes are abbreviated as in Table A.3.

CRF	Background death rate
All causes (all)	All causes
Lower respiratory infections (LRI)	Lower respiratory infections
Lung cancer (LC)	Tracheal, bronchus, and lung cancer

Chronic obstructive pulmonary disease (COPD)	Chronic obstructive pulmonary disease
Diabetes	Diabetes mellitus type 2
Stroke	Stroke
Ischemic heart disease (IHD)	Ischemic heart disease

Table A.3. Translation dictionary between death cause names in the CRF sources and in the background death rate data. Highlighting where terminology does not match exactly.

3. Evaluating the economic cost of the health impacts

An economic valuation of human health impacts represents an estimate of what would be an acceptable cost for avoiding the population level health impact in question. The approach used in this paper measures people's own willingness to pay to avoid a risk of death. This report has shown that a large number of people in Taiwan are exposed to the health impacts of poor air quality.

The approach to this willingness-to-pay study for air pollution followed here is recommended by OECD (2012)[37] and based on a comprehensive survey of willingness-to-pay studies. The observed difference in willingness-to-pay to avoid mortality risks for children and adults is taken into account. The causes of death covered in the health impact assessment result in average loss of 20-25 life years for each death for adults and over 80 years for small children[38], so willingness-to-pay studies covering healthy adults and children are applicable.

The estimated annual costs over time are adjusted and discounted to the present by applying a discount rate of 5% and assuming a GNI per capita growth rate of 4.7% (2002-2012 average, based on World Bank statistics), and an income elasticity of 0.8 over time, implying 3.8% annual increase in willingness to pay.

	Central	Low	High	Unit	Reference
VSL, OECD 2005	3	1.5	4.5	2005USDmln	OECD 2012
Income elasticity of VSL	0.8	0.9	0.4	2005USDmln	OECD 2012
Children VSL compared to adults	2	1.5	2		OECD 2012-en
OECD GNI per capita 2005	35,115	35,115	35,115	2005USD	World Bank
U.S. GDP deflator 2005-2018	1.302326627	1.302326627	1.302326627		U.S. Bureau of Labor Statistics
Taiwan GNI 2018	25,501	25,501	25,501	2018USD	https://eng.stat.gov.tw/ct.asp?xItem=37408&CtNode=5347&mp=5
USD-NTDmln exchange rate 2018	30.15407239	30.15407239	30.15407239		https://eng.stat.gov.tw/ct.asp?xItem=37408&CtNode=5347&mp=5

[37] OECD 2012: Mortality Risk Valuation in Environment, Health and Transport Policies. DOI:10.1787/9789264130807-en
[38] GBD 2017 Mortality Collaborators. *Global, regional, and national age-sex-specific mortality and life expectancy, 1950–2017: a systematic analysis for the Global Burden of Disease Study 2017.* The Lancet. 8 Nov 2018;392:1684-735. http://dx.doi.org/10.1016/S0140-6736(18)31891-9.

VSL, Taiwan, 2018, adults	91.2	44.2	155.5	2018NTDmln	
VSL, Taiwan, 2018, children	182.4	66.3	311.0	2018NTDmln	

Table A.4. Deriving the value of statistical life (VSL) for Taiwan using the approach recommended by the OECD.

Appendix 3. Supplementary Figures

Anomaly plots showing the projected near-surface pollutant concentration reduction achieved by Scenario 1 and Scenario 2 are shown in figures A1 to A7.

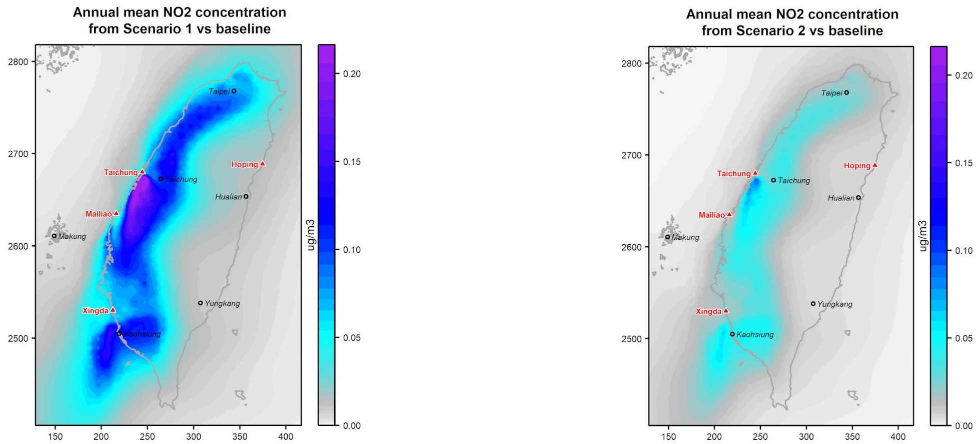

Figure A1. Annual Mean NO_2 concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.

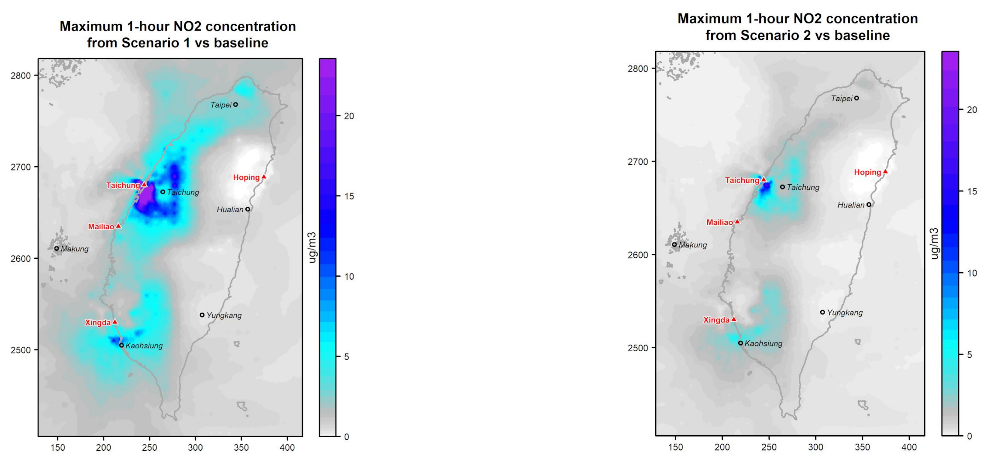

Figure A2. Maximum 1-hour Mean NO_2 concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.

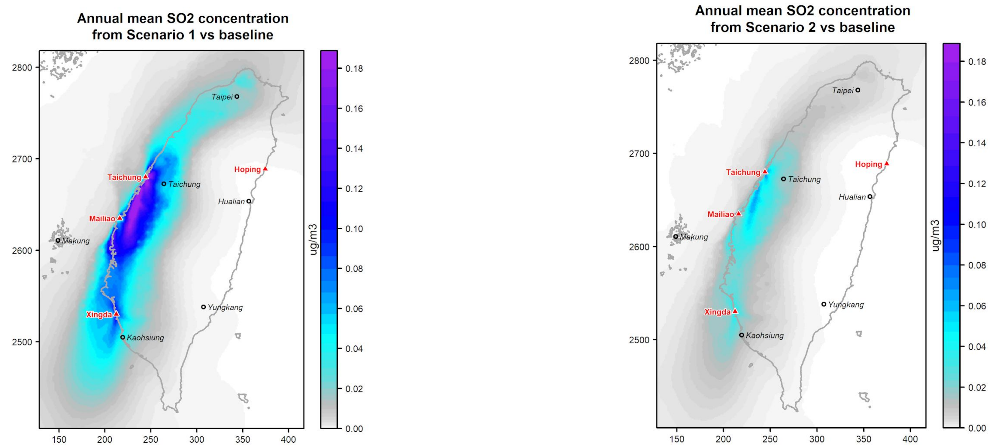

Figure A3. Annual Mean SO_2 concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.

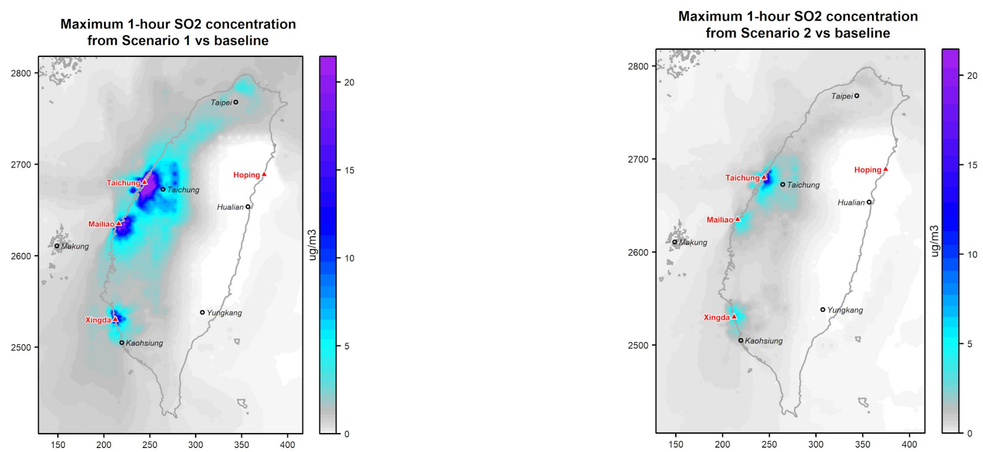

Figure A4. Maximum 1-hour Mean SO_2 concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.

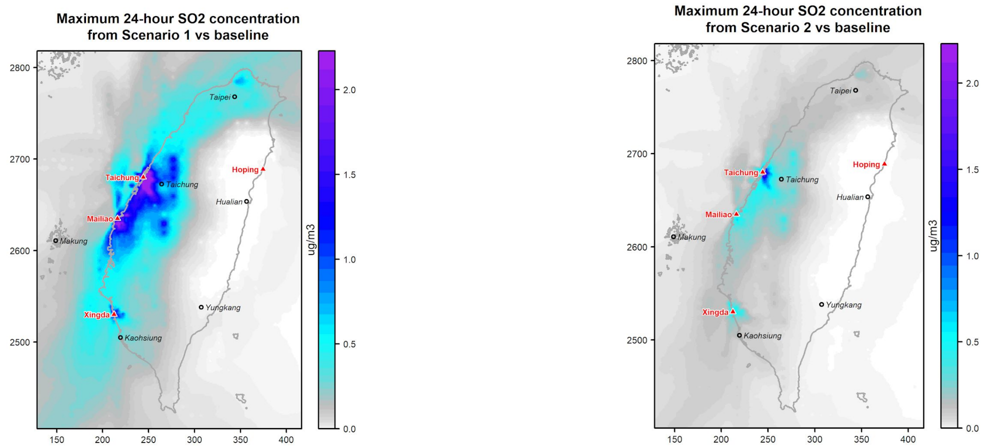

Figure A5. Maximum 24-hour Mean SO_2 concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.

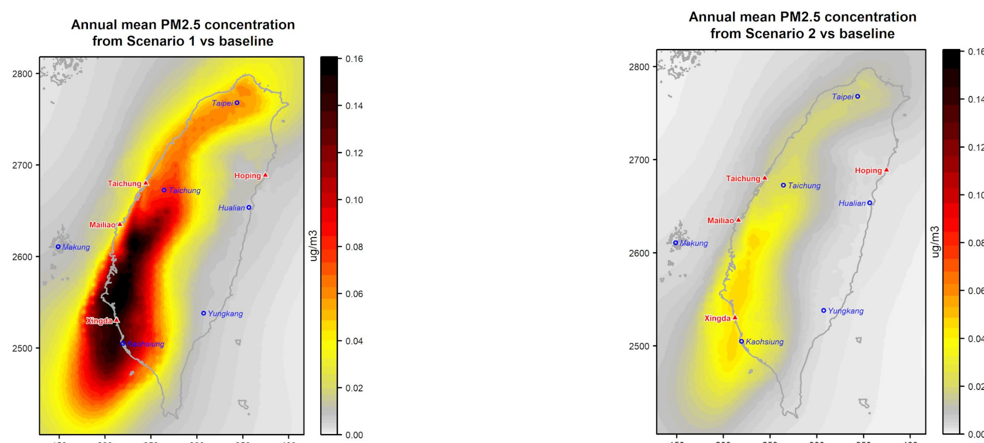

Figure A6. Annual Mean $PM_{2.5}$ concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.

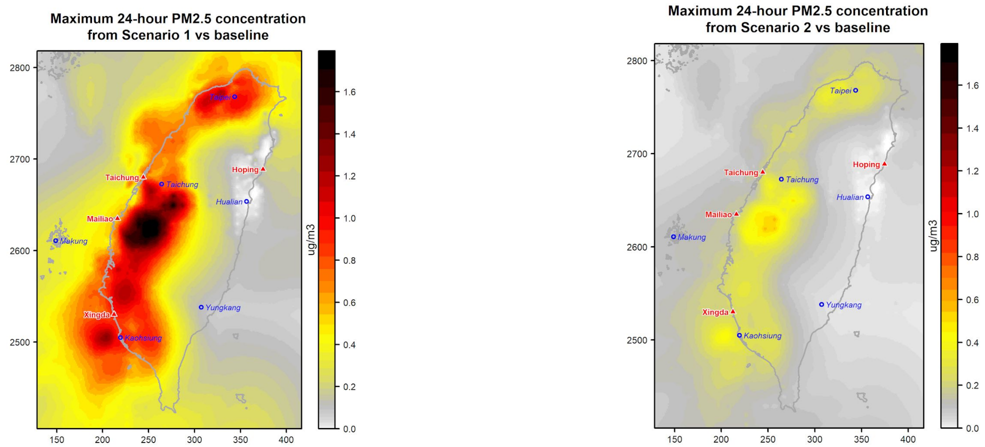

Figure A7. Maximum 24-hour Mean $PM_{2.5}$ concentration across Taiwan. Left: Difference of Baseline and Scenario 1. Right: Difference of Baseline and Scenario 2. The studied plants are marked as a red triangle.