TOXIC AIR: THE PRICE OF FOSSIL FUELS

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GREENPEACE

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Cover image: Air Pollution Protest in Bangkok ©Wason Wanichakorn/ Greenpeace

This page: A shepherdess watches over her flock of sheep that graze near a coal power plant in Jepara, Central Java ©Kemal Jufri/Greenpeace

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‘We want clean air’ action in Hong Kong
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EXECUTIVE SUMMARY

This report reveals the cost of air pollution from fossil fuels and highlights solutions that can protect our health and benefit our communities. Air pollution generated by burning fossil fuels is attributed to approximately 4.5 million premature deaths worldwide every year, the report shows. Air pollution increases the incidence of chronic and acute illnesses and contributes to millions of hospital visits and billions of work absences due to illness each year. It also damages our economies and the environment.

For the first time, Greenpeace Southeast Asia and the Centre for Research on Energy and Clean Air (CREA) have quantified the global cost of air pollution from fossil fuels, finding that it has reached an estimated US$8 billion per day, or 3.3% of the world's GDP. While coal, oil and vehicle companies continue to push outdated technologies, our health and our communities are paying the price.

The economic cost of air pollution reflects pollution concentrations, population size and the availability and cost of healthcare. We found that the China Mainland, the United States and India bear the highest costs from fossil fuel air pollution worldwide, at an estimated US$900 billion, US$600 billion and US$150 billion per year, respectively.

We estimate that exposure to $PM_{2.5}$ and ozone from fossil fuels is responsible for 7.7 million asthma-related trips to the emergency room each year. Exposure to fossil fuel generated fine particulate matter ($PM_{2.5}$) alone is attributed to an estimated 1.8 billion days of sick leave annually.

Air pollution is a major health threat to children, particularly in low income countries. Worldwide an estimated 40,000 children die before their fifth birthday because of exposure to $PM_{2.5}$ pollution. We found that air pollution from fossil fuel-related $PM_{2.5}$ is attributed to an estimated 2 million preterm births each year.

Yet while toxic air pollution is a global threat, the solutions are increasingly available and affordable. Moreover, many solutions to fossil fuel air pollution are also the solutions to climate change. Clean transport and renewable energy not only bring significant reductions in toxic pollutants such as $PM_{2.5}$, NO_x and ozone, but also help to keep climate change-causing greenhouse gases out of the atmosphere.

A phaseout of existing coal, oil and gas infrastructure brings major health benefits due to the associated reduction in air pollution. Research shows that the closure of coal-fired power plants can yield health benefits that exceed the value of electricity generated.[1] According to a study published in the Proceedings of the National Academy of Sciences, an expanded fossil fuel phaseout and investment in clean energy sources could reduce premature deaths related to air pollution worldwide by up to nearly two thirds[2].

In addition, a transition to affordable and carbon neutral transport is critical to ensuring healthy cities. Effective public transport systems and good walking and cycling infrastructure enable mobility, reduce air pollution and greenhouse gas emissions, and correlate with a decrease in rates of cardiovascular disease, cancer, obesity, diabetes, mental illness, and respiratory disease[3].

One of the most important ways that governments can catalyze sustainable transport is to set a phase-out date for diesel, gas, and petrol cars, and to introduce comprehensible and affordable public transport, with safe walking and cycling infrastructure. We need to move away from private cars as the primary mode of transport, and initiatives like car-free days allow us to imagine what our cities would look like without traffic and pollution.

The transition to renewable energy is essential both to prevent catastrophic climate change and to protect our health. While fossil fuel companies continue to market outmoded technologies, our communities pay the price. A just transition to renewable energy is possible, but we can't afford to delay any longer.

1.0 INTRODUCTION

This report, 'Toxic air: The price of fossil fuels', assesses the impacts on global health and the economic cost of air pollution from the continued burning of fossil fuels such as coal, oil and gas. Using data published in 2019 – including the first study to assess the contribution of fossil fuels to global air pollution and health[4] – the report provides a global assessment of the health impact of air pollution from fossil fuels in 2018 and a first-of-its-kind estimate of the associated economic cost. Case studies relating to transport and power generation show that reducing air pollution is feasible, achievable and cost effective.

This report uses the most recent evidence and data on pollution levels, health effects and demographics to quantify the effects of air pollution on global and regional levels. The analysis includes an estimate of the financial cost of the health burden on the global economy. Using case studies, the report discusses how the phaseout of fossil fuels will have the co-benefit of mitigating climate change and reversing some of the most pressing global health problems[5].

1.1 Air pollution: a brief overview

The primary focus of 'Toxic air: The price of fossil fuels', is the impact of air pollution from burning fossil fuels on human health and the associated financial costs. The study is limited to the pollutants; fine particulate matter (abbreviated to $PM_{2.5}$), ozone (O_3) and nitrogen dioxide (or NO_2), and only that pollution which is emitted by fossil fuel combustion.

1.1.1 What are the key air pollutants?

This report only considers the impact of fossil fuel-related air pollution and only those pollutants for which there are well understood relationships between changes in pollutant concentration and health impacts. The following pollutants are included:

- **Nitrogen oxides.** When fossil fuels are burned in air, nitrogen oxides (NO and NO_2, collectively referred to as NO_x) are created from molecular nitrogen in the air and in the fuel that is being burned. NO_x pollution, along with sulfur dioxide, which is also produced when fossil fuels are burned, reacts with water to form acid rain, snow and fog, and with other substances to form particulate matter (see section 1.1.1) and smog. The health impacts of exposure to nitrogen oxides include cardiovascular diseases, exacerbated symptoms of asthma, chronic obstructive pulmonary disorder and other respiratory diseases[6,7]. Acid rain is detrimental to plants and animals.
- **Ozone.** Ozone (O_3) is found in the stratosphere, one of the Earth's protective atmospheric layers. Stratospheric ozone protects the Earth's surface from ultraviolet radiation from the sun, but ozone also forms at near-ground level, where it is an air pollutant that causes smog. Ground level ozone forms when NO_x pollution reacts with chemicals called volatile organic compounds. Ozone pollution causes acute human health problems, including chest pain, throat irritation and inflammation of the airways. Ozone can also impair lung function and increase the symptoms of bronchitis, emphysema and asthma[8]. It also adversely affects vegetation and crops.
- **Particulate matter.** Particulate matter, (also known as particle pollution or PM,) is a term used to describe extremely small particles and liquid droplets in the atmosphere. In relation to exposure to particulate matter, the World Health Organisation says: "There is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur" [9]. These particles can be a combination of different chemicals and are classed according to particle size: PM_{10}; $PM_{2.5}$; and ultrafine particles (Figure. 1).
    a. **Ultrafine definition.** Ultrafine particulates have no formal definition but the general consensus is that they are any particles with an aerodynamic diameter of ≤ 0.1 μm. Ultrafine particles are respirable, which means that they are small enough to reach the gas exchange region of the lungs.

b. $PM_{2.5}$ definition. $PM_{2.5}$ refers to any particulate matter with an aerodynamic diameter that measures ≤ 2.5 μm, including ultrafine particles. As with ultrafine particulates, $PM_{2.5}$ particles are respirable, which means that they are small enough to reach the gas exchange region of the lungs[10].

c. PM_{10} definition. PM_{10} particles are ≤ 10 μm in diameter[11]. These particulates are inhalable and can lodge in the respiratory tract[12].

1.1.2 What are the sources of air pollution?

Natural
Particulate matter occurs naturally in the environment. Airborne desert dust, sulfates, volcanic emissions and organics released by vegetation are natural sources of PM[14]. Nitrogen oxides are released into the environment from natural sources such as microbial processes in soils, lightning and forest fires[15]. Many of these processes can be exacerbated by human-induced global warming and environmental changes.

Anthropogenic
Human activities that contribute significant quantities of particulate matter include road- and non-road transport, including shipping and air traffic; public energy production by fossil fuel power plants; commercial and residential combustion sources (cooking and heating); industrial activity; biomass burning (forest, shrub, grass and agricultural waste); and agriculture. In urban areas, traffic and combustion are the primary sources[16] of $PM_{2.5}$.

Nitrogen oxides are released during any combustion reaction, particularly at high temperatures. The primary anthropogenic sources of NO_x are vehicles, non-road vehicles, (for example, construction equipment,) industrial sources such as power plants, turbines, industrial boilers and cement kilns, boats and heating for buildings[17].

Primary and secondary pollutants
Air pollutants are classed as primary if they are emitted directly from the source – a factory chimney or vehicle exhaust, for example. Secondary air pollutants are formed when a chemical reaction occurs in the atmosphere involving a primary air pollutant. Ozone is a secondary air pollutant created when oxides of nitrogen react with a group of chemicals called volatile organic compounds. Some particulate matter pollution is secondary pollution. For example, sulfur dioxide can oxidise to form sulfuric acid, which can then produce ammonium sulfate particles if it reacts with ammonia.

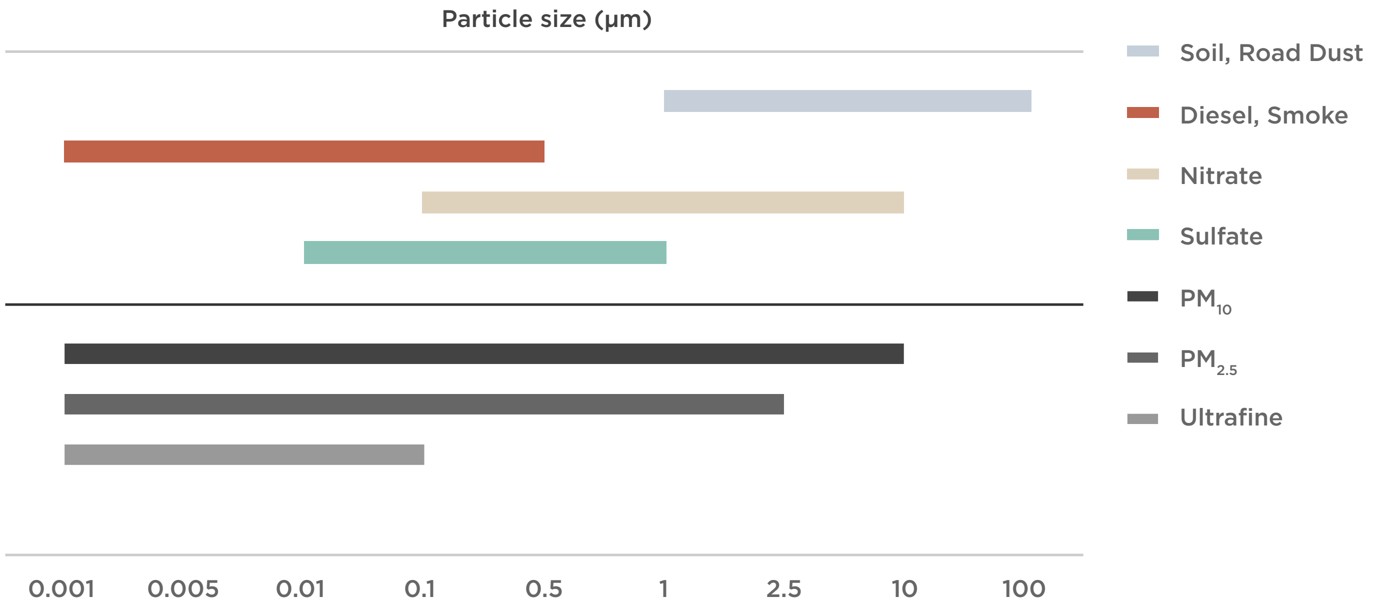

Figure 1. A graphic representation on a logarithmic scale showing example sources of different sized air pollution particles (blue, red, beige, green) and the size fractions of particulate matter to which they contribute (dark to light grey)[13].

1.2 Air pollution from burning fossil fuels

Burning fossil fuels – primarily coal, oil and gas – emits pollutants, contaminating the air that we breathe and leading to adverse health effects. Major sources responsible for emitting pollutants into the atmosphere including power generation, transport, (including petrol and diesel vehicles), residential energy use, agriculture and industry.

Historically, energy from fossil fuels has dominated power generation (Figure. 2), but as the cost of establishing and maintaining renewable sources of power (such as wind and solar) continues to fall, these options are now frequently less expensive than the fossil fuel alternative.

Research by the International Renewable Energy Agency published in 2018 took into account the lifetime cost of electricity in its calculations of cost comparisons to generate power from renewable sources versus fossil fuels. Although in most parts of the world newly commissioned power plants that use renewable sources, such as wind and solar, will be cheaper or at a similar cost than from fossil fuels, including coal, oil and gas[18], companies continue to push outdated technologies with the outcome that fossil fuels continue to dominate, creating air pollution when cleaner alternatives are readily available.

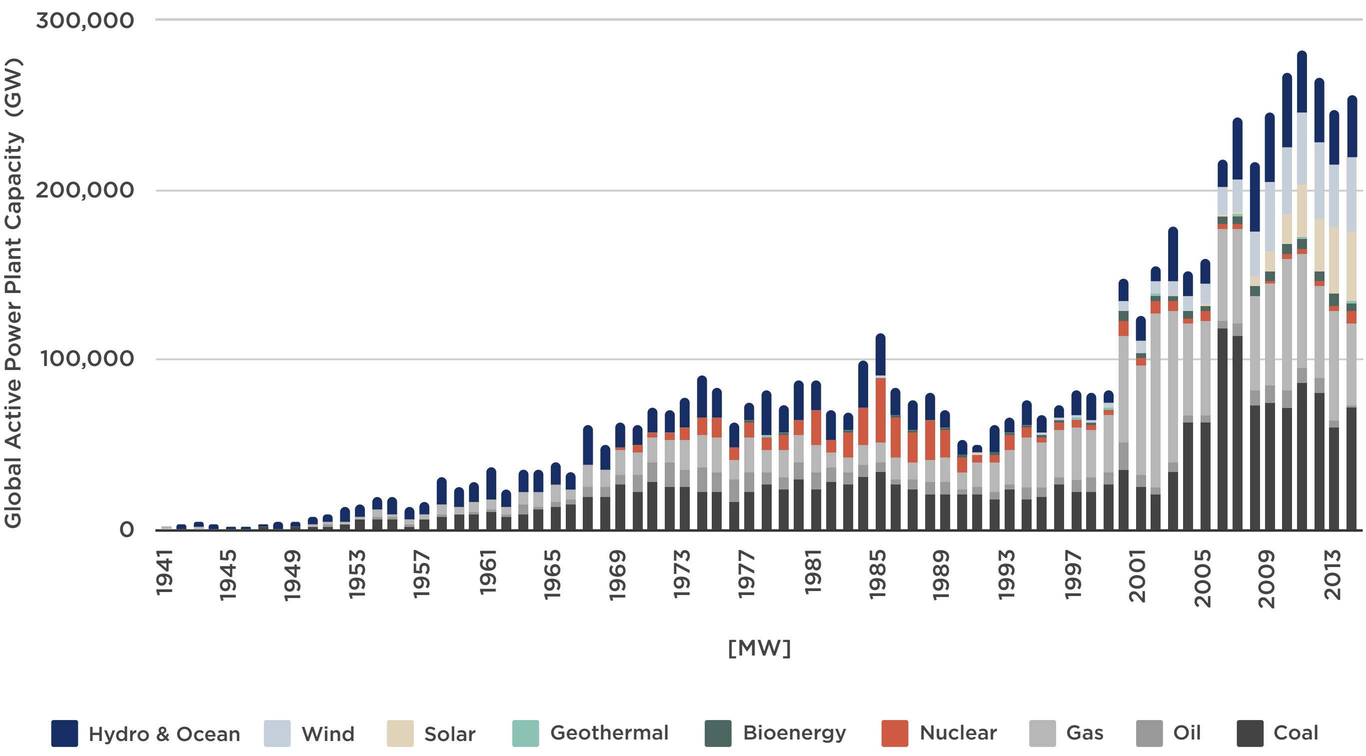

Figure 2: Global active power plant capacity added per year, still active in 2014. Fossil fuel use has dominated energy supplies for decades, but the use of renewable technologies has been rapidly expanding, particularly since the mid-2000s[19].

1.3 Air pollution, health and cost

Air pollution affects physical and mental health because it contributes to acute and chronic diseases that can reduce quality of life. Evidence from public health studies suggests that exposure to an air pollutant or combination of air pollutants, such as $PM_{2.5}$, NO_2 or ozone, is associated with increased incidence of diseases including ischaemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer, lower respiratory infections, premature birth (preterm birth), type II diabetes, stroke and asthma[20,21,22,23]. Health impacts from air pollution generate economic costs from the cost of treatment, management of health conditions, and from work absences.

The properties and effects of air pollution vary from country to country; different locations are affected by different pollutants, pollution sources and environmental conditions. Combined with differences in population and lifestyle, the health impacts from air pollution change significantly depending on the geographical location[24,25,26]. For example, a computer modelling study[27] looked at seven different sources of $PM_{2.5}$ and ozone air pollution: industry; land traffic; residential and commercial energy; biomass burning; power generation; agriculture; and natural. Using the model, the researchers calculated premature mortality resulting from air pollution generated by each of the seven sectors. Of premature deaths attributed to air pollution globally in 2010, almost one-third were attributable to exposure (while outdoors) to air pollution from residential and commercial energy[28], which was the principal source of air pollution-related premature deaths in India and China Mainland. Globally, land traffic was attributable for 5% of air pollution-related premature deaths and power generation for 14%. Countries where air pollution from land traffic emissions were particularly high included the US, Germany, Russia, Turkey and Japan. The contribution of power generation to premature mortality was particularly high in the US, Russia, Turkey, China Mainland and Japan[29].

The World Health Organisation (WHO) has created guidelines that describe the level of air pollution above which there is strong evidence of negative health impacts[30]. These guidelines are derived from the latest available evidence on the health effects of ambient air pollutants and undergo regular review[31]. In 2019, around 91% of the global population lived in places where levels of air pollution exceeded the WHO guidelines[32].

1.4 Air pollution and climate

The phaseout of fossil fuels and switch to renewable forms of energy is beneficial both for reducing air pollution and mitigating anthropogenic climate change[33]. Events that may be affected by climate change such as sandstorms, wildfires and heat waves can worsen air pollution by, for example, increasing the quantity of particulate matter in the air. Reducing the health burden attributed to air pollution while simultaneously reducing emissions of climate pollutants can be achieved by, for example, removing coal from the energy industry or limiting emissions from the transport sector[34].

Air pollution and the climate crisis are clearly linked. Replacements for the coal, oil and gas that are currently used to generate power, for transport and for domestic heating will need careful consideration to ensure that alternative combustion processes are avoided. For example, if future energy generation is obtained by burning biomass the likely scenario is increased emissions of harmful air pollutants such as $PM_{2.5}$[35]. The pathways chosen to meet greenhouse gas-reduction targets must champion renewable technology and resource efficiency without negatively affecting air quality.

2.0 THE ECONOMIC COST OF AIR POLLUTION FROM FOSSIL FUELS

2.1 Introduction

This section presents the first global assessment of the economic burden of health impacts from fossil fuel air pollution. Analysis commissioned by Greenpeace Southeast Asia and carried out by the Centre for Research on Energy and Clean Air (CREA) has estimated the global and national impact of air pollution from fossil fuels. This chapter presents the findings from the analysis. Air pollution from non-fossil fuel sources (see section 1.1.2) is not included in the analysis.

The CREA/Greenpeace analysis suggests that air pollution from burning fossil fuels costs an estimated 3.3% (95% confidence interval 2.4–4.7%) of global gross domestic product, equivalent to US$8 billion per day (95% confidence interval US$5.5–11.0bn) and 12,000 (95% confidence interval 9,000–17,000) premature deaths every day.

The assessment incorporates recent research that quantifies the contribution of fossil fuels to global air pollution levels. It uses published global datasets describing surface level concentrations of $PM_{2.5}$, ozone and NO_2 to perform a health impact assessment and subsequent cost calculation for the year 2018. Full details of the methodology are provided in Appendix 1.

The health and economic impacts included in the CREA/Greenpeace analysis only consider fossil fuel-related air pollution and are shown in Table 1. Only those impacts for which there is sufficiently robust data relating pollutant concentrations to population level health impacts are included. Therefore, these figures represent only a proportion of the total burden of all air pollution. Finally, because not all real world health impacts from fossil fuel air pollution are included, the analysis presented in this chapter is a conservative estimate of the global impact of fossil fuels on air pollution, health and the economy.

The health impacts are determined by combining pollutant concentration maps[36,37] representing the year 2018, with country or region-level demographic data and health statistics. Concentration response functions for each pollutant are used to relate a pollutant concentration to the response or impact of that pollutant on a population. Published concentration–response functions, described in Appendix 1, were used to calculate the impact of the mapped fossil fuel air pollution at a population level for the calendar year 2018. Using research carried out by the World Health Organization's project called 'Health risks of air pollution in Europe' (HRAPIE)[38], it is possible to estimate the number of working days lost through exposure to $PM_{2.5}$, but statistics are not available to calculate the impact of other air pollutants on work absences. The concentration response functions used to calculate the incidence of the health and economic outcomes shown in Table 1. Full details of the economic impact calculations used in the CREA/ Greenpeace analysis are provided in Appendix 1.

Previous studies have estimated global and regional mortality and disease incidence rates resulting from exposure to air pollution and fossil fuel derived air pollution. The methodology applied in this work builds on recent scientific findings and models of the health risks of air pollution exposure. An updated model of mortality risks due to outdoor $PM_{2.5}$ pollution in 2018 found substantially higher risks than earlier studies and consequently revised the estimates of premature deaths upwards[39]. A new cohort study on ozone similarly led to a large increase in deaths attributed to ozone pollution in 2017[40]. For these reasons, the estimates of death and disease in our study exceed many earlier results, sometimes leading to the number of deaths attributed to fossil fuels exceeding the total number of deaths from air pollution reported in some earlier studies. Full details of the health and economic impact calculations used in the CREA/Greenpeace analysis are provided in Appendix 1.

Table 1: Impacts included in the analysis by pollutant type*.

Pollutant	**Impact of pollutant exposure**	**Outcome**
NO_2	Asthma	Asthma prevalence
		New asthma cases in Children
	Non-communicable diseases and lower respiratory infesctions	Premature deaths
		Years of life lost
Ozone	Chronic obstructive pulmonary disease	Premature deaths
		Years of life lost
	Asthma	Emergency room visits
$PM_{2.5}$	Work absences	Work absences
	Chronic obstructive pulmonary disease	Premature deaths
	Diabetes caused by chronic diseases (Years lived with disability)	
	Ischaemic heart disease	
	Lung cancer	
	Lower respiratory infections	
	Lower respiratory infections in children under 5	
	Other non-communicable diseases and lower respiratory infections	
	Stroke	
	Asthma	Emergency room visits
	Preterm birth	Preterm birth
	Chronic obstructive pulmonary disease	Years of life lost
	Diabetes caused by chronic diseases (Years lived with disability)	
	Stroke	
	Lower respiratory infections in children under 5	
	Non-communicable diseases and lower respiratory infections	

*Although many health impacts are linked to $PM_{2.5}$, NO_2 and ozone, only those health impacts for which a robust relationship exists between changes in pollutant concentration and the incidence of disease have been included in the study.

2.2 Health impacts and costs

2.2.1 Health

The CREA/Greenpeace analysis suggests that an estimated 3 million premature adult deaths each year are attributed to cardiovascular diseases, respiratory diseases and lung cancer through exposure to $PM_{2.5}$ air pollution from fossil fuels. An estimated 500,000 premature deaths from chronic diseases are attributed to fossil fuel-related NO_2 pollution and 1 million premature deaths are attributed to fossil fuel-related ozone pollution annually. Combined, total premature deaths per year attributable to fossil fuel-related air pollution is estimated at 4.5 million.

The data calculated for this report estimates that 40,000 children may die before their fifth birthday due to illnesses related to exposure to $PM_{2.5}$ from fossil fuels and shows that those deaths occur mainly in low-income countries. The loss of a child is tragic and devastating to the families affected. In economic terms, infant mortality has a high fiscal cost to society because that child is prevented from contributing to society in adulthood (Table 2).

Millions of people around the world are living with asthma and other chronic respiratory diseases where exposure to pollution from fossil fuel combustion is a contributing factor. Chronic diseases can lead to substantial healthcare costs and prevent people from participating in the workforce. Exposure to $PM_{2.5}$ is the leading cause of health and economic impacts arising from air pollution and in 2018 contributed to a higher number of premature deaths than those we can attribute to exposure to NO_2 and ozone combined (Fig. 3).

Doctors against diesel campaign action in London
©David Mirzoeff

Table 2: The estimated global impact of fossil fuel-related air pollution on selected health and economic outcomes by pollutant in 2018. Provided are the upper and lower bounds of a 95% confidence interval (low, high) and a central estimate.

Pollutant	Impact	Total Number			Total Cost (Million US Dollars)		
		Low	Central	High	Low	Central	High
NO_2	**Premature Deaths**	300,000	500,000	1,100,000	-	-	-
	Years of Life Lost	4,900,000	8,900,000	19,400,000	185,000	335,000	732,000
	New Cases of Asthma in Children	1,800,000	4,000,000	5,200,000	-	-	-
	Number of Children Living with Asthma Due to Air Pollution	7,800,000	16,100,000	19,600,000	8,000	16,000	19,000
Ozone	**Premature Deaths**	600,000	1,000,000	1,400,000	-	-	-
	Years of Life Lost	9,700,000	15,400,000	21,800,000	247,000	379,000	523,000
	Asthma (Emergency Room Visits)	2,800,000	5,600,000	5,600,000	500	1,000	1,000
$PM_{2.5}$	**Premature Deaths**	2,300,000	3,000,000	3,700,000	-	-	-
	Years of Life Lost	48,700,000	62,700,000	77,700,000	1,385,000	1,766,000	2,173,000
	Asthma (Emergency Room Visits)	1,800,000	2,700,000	3,800,000	200	350	500
	Preterm Births	1,000,000	2,000,000	2,100,000	47,000	91,000	96,000
	Work Absences	1,503,200,000	1,755,200,000	2,002,200,000	86,000	101,000	115,000
Total	**Premature Deaths**	3,200,000	4,500,000	6,200,000	-	-	-
	Years of Life Lost	63,300,000	87,000,000	118,900,000	1,817,000	2,480,000	3,428,000

*Low, central and high estimates are provided representing a 95% confidence interval.

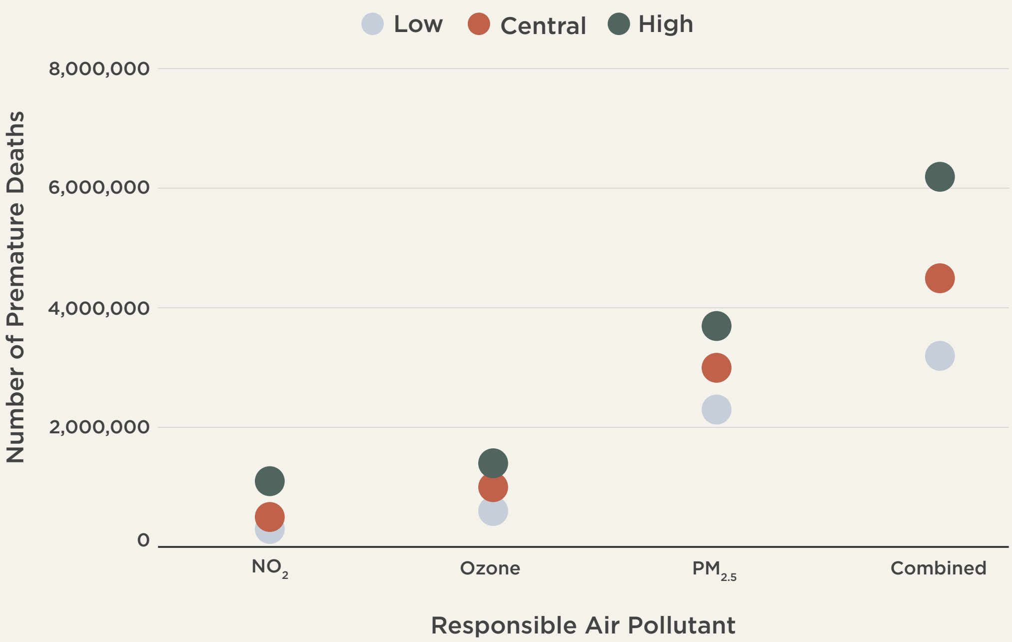

Figure 3: The estimated global number of premature deaths from exposure to fossil fuel-related air pollution in 2018.

Air pollution and traffic in London
©Elizabeth Dalziel/Greenpeace

2.2.2 Economic cost

Data generated by the CREA/Greenpeace model suggests that an estimated annual cost of US$2.9 trillion (central estimate), equivalent to 3.3% of global GDP or US$8 billion per day, is attributed to air pollution from fossil fuels (Table 3, Figure 4). These costs are the result of respiratory and non-communicable diseases made more likely by elevated pollution levels. An economic valuation of the years of life lost through premature death is also included. The impact of premature death can be quantified using a measure known as 'years of life lost'. The personal tragedy of a premature death also brings an economic cost through lost contributions to society and economy. This means that when premature deaths occur, especially in children and younger people, the economic cost can be large.

Costs of US$350 billion and US$380 billion are attributed to NO_2 and ozone air pollution from fossil fuels respectively, each equivalent to 0.4% of global GDP.

$PM_{2.5}$ air pollution leads to the greatest health impact and the greatest financial cost of the three pollutants. $PM_{2.5}$ from fossil fuels is attributed to increased work absences, causing an estimated 1.8 billion (central estimate) days of work absences annually worldwide (Table 3).

Table 3: The estimated annual global cost of fossil fuel-related air pollution in 2018*

Pollutant	Impact	Low	Central	High
NO_2	Total Cost (Billion US$)	192	351	750
	% GDP	0.2%	0.4%	0.9%
Ozone	Total Cost (Billion US$)	248	380	524
	% GDP	0.30%	0.40%	0.60%
$PM_{2.5}$	Total Cost (Trillion US$)	1.6	2.2	2.7
	% GDP	1.8%	2.5%	3.1%
	Work Absences (Days)	1,503,200,000	1,755,200,000	2,002,200,000
Combined	Total Cost (Trillion US$)	2.09	2.9	4.0
	% GDP	2.4%	3.3%	4.7%

*Low, central and high estimates are provided representing a 95% confidence interval

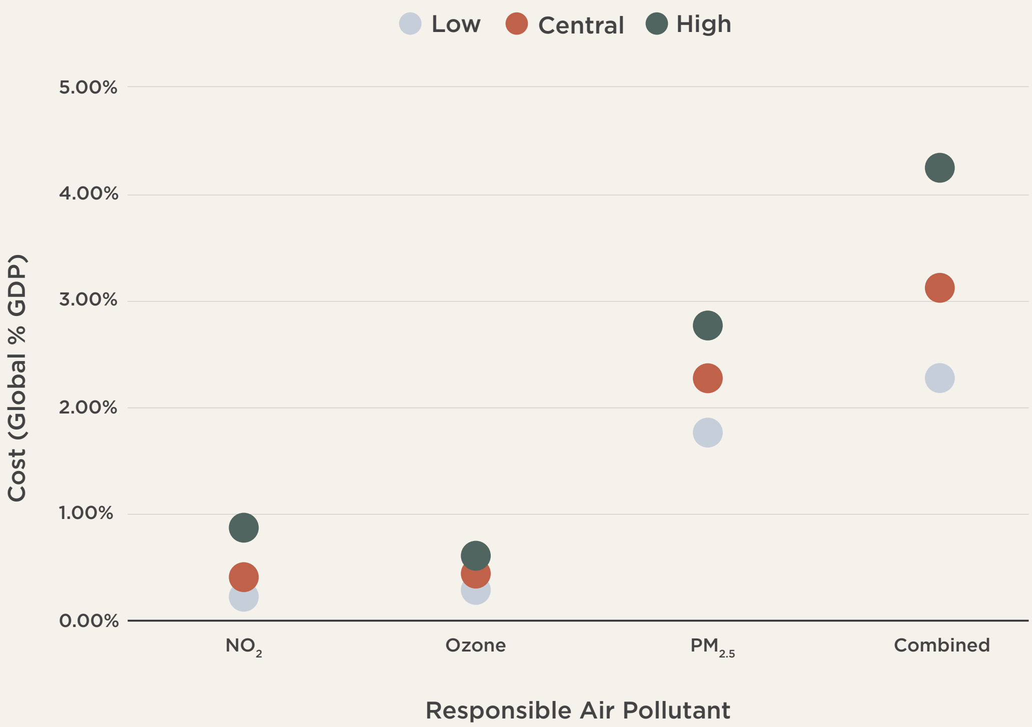

Figure 4: The estimated annual global cost of fossil fuel-related air pollution in 2018. Low, central and high estimates are provided, representing a 95% confidence interval.

2.3 Regional examples of the cost of air pollution

This section presents findings generated by the CREA/Greenpeace data in particular relevance to different global regions.

2.3.1 Health

The health impact of fossil fuel air pollution in a country or region is determined by factors including the nature and distribution of pollution sources, the local environment, weather conditions, background rates of disease not related to air pollution, population size and population density, among others.

The data generated in the CREA/Greenpeace analysis includes the projected number of asthma-related emergency room (ER) visits attributable to $PM_{2.5}$ and ozone. Globally, the findings estimate 7.7 million (confidence 4.8–10.0 million) asthma-related ER visits annually. Of these, 37,000 (24,000–47,000) ER visits are in Russia; 62,000 (37,000–83,000) in South Africa; 196,000 (125,000–248,000) in the US; and 266,000 (166,000–340,000) in Indonesia, for example. A breakdown of cost and premature death data by location is provided in Appendix 2.

Approximately 2 million (1,032,000–2,093,000) preterm births worldwide are attributed to $PM_{2.5}$ exposure as a result of fossil fuel use. Of these, an estimated 350,000 (184,000–367,000) are in China Mainland; 14,000 (6,700–14,500) are in South Africa; 981,000 (517,000–1,031,000) are in India; and 11,000 (6,000–12,000) are in Thailand.

The incidence of stroke has been linked to $PM_{2.5}$ exposure and the CREA/Greenpeace data estimates that 600,000 (268,000-904,000) deaths annually can be attributed to stroke relating to fossil fuel derived $PM_{2.5}$ exposure.

Across the EU, around 400,000 annual premature deaths are attributed to exposure to air pollution from fossil fuel use. Of those deaths three-quarters are related to $PM_{2.5}$ exposure with the remainder being related to NO_2 and ozone exposure (Table 4, Figure 5).

Table 4: The estimated number of premature deaths in the European Union attributable to fossil fuel air pollution in 2018. Low, central and high estimates are provided representing a 95% confidence interval

EU	Premature deaths in 2018		
	Low	**Central**	**High**
Total	289,000	398,000	567,000
$PM_{2.5}$	229,000	295,000	367,000
NO_2	38,000	69,000	152,000
Ozone	22,000	34,000	48,000

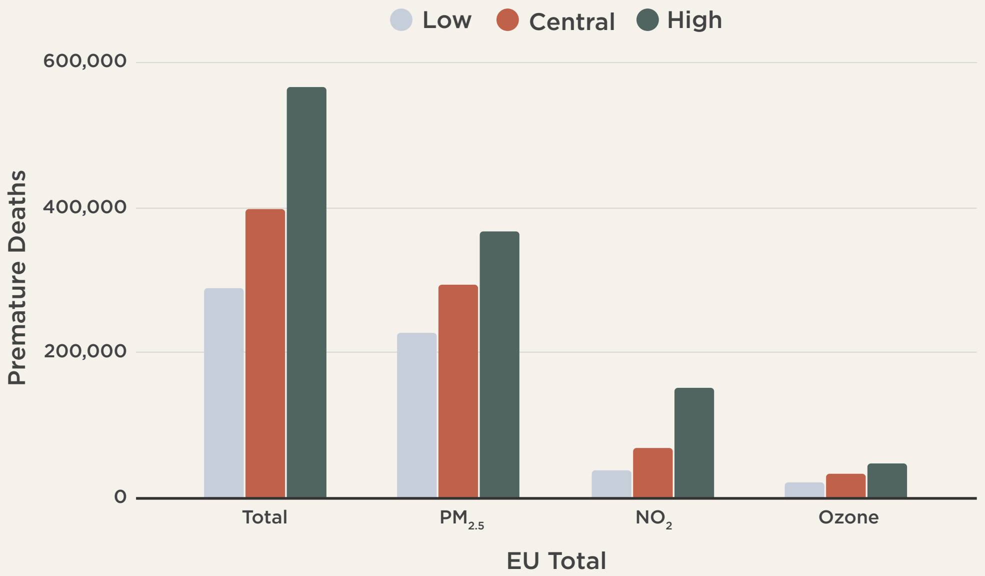

Figure 5: Estimated premature deaths in the EU attributable to fossil fuel air pollution by pollutant (2018). Low, central and high estimates are provided representing a 95% confidence interval.

In East Asia the absolute number of early deaths attributed to air pollution is dominated by those in China Mainland. Despite rapid improvements in $PM_{2.5}$ air quality since 2015[41], pollution continues to affect a large proportion of the population. Annually 1.8 million (1.3-2.5 million) premature deaths are projected across China Mainland. The estimated number of annual premature deaths relating to fossil fuel emissions is 40,000 (28,000-61,000) in South Korea, 16,000 (12,000-24,000) in Taiwan and 100,000 (75,000-150,000) in Japan.

Across East Asia, the majority of premature deaths are attributed to $PM_{2.5}$ exposure (Figure 6). Chronic obstructive pulmonary disorder (COPD) is a leading cause of early deaths. Data from the present analysis attribute 582,000 (366,000-827,000) deaths to COPD-related to $PM_{2.5}$ exposure from fossil fuels in China Mainland, approximately 40% of the global incidence. In South Korea 5000 (3,000-7,000) premature deaths from COPD are projected with 4,000 (2,000-6,000) in Taiwan; and 15,000 (9,000-22,000) in Japan.

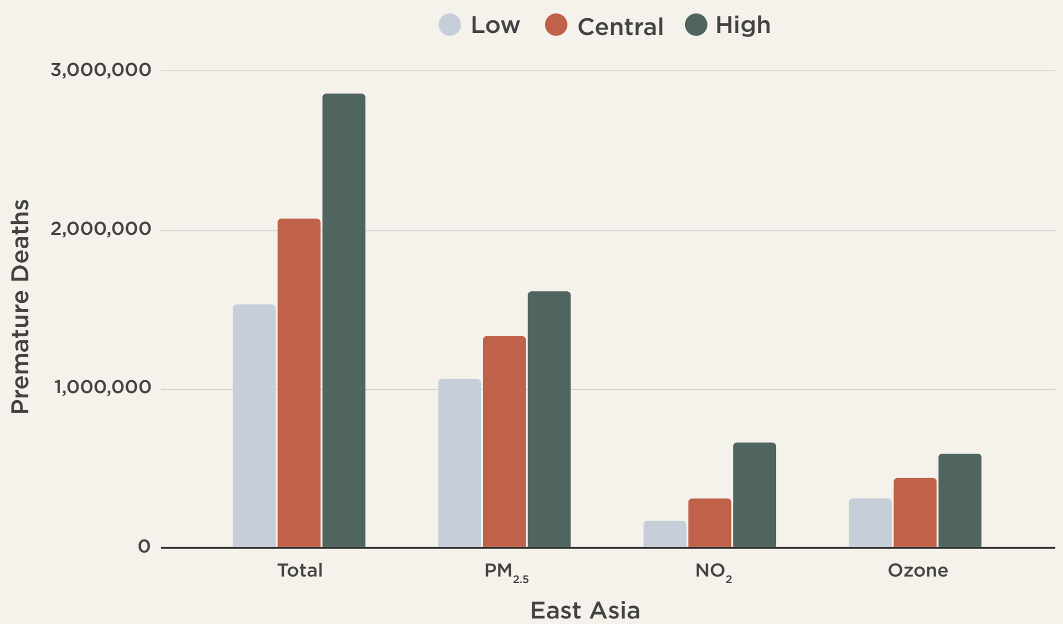

Figure 6: Estimated premature deaths in East Asia attributed to fossil fuel air pollution by pollutant (2018). Low, central and high estimates are provided representing a 95% confidence interval.

Premature deaths attributed to fossil fuel air pollution in the Southeast Asian nations of Vietnam, Laos, Thailand, Myanmar, Singapore, Cambodia, Malaysia, Indonesia, Philippines, Brunei and Timor Leste are shown in Table 5 and Figure 7. The greatest number of premature deaths are projected in Indonesia and Vietnam, where deaths from COPD attributable to $PM_{2.5}$ are estimated to be 17,000 (10,000–25,000) and 10,000 (5,000–17,000) respectively.

Table 5: Estimated premature deaths in Southeast Asia attributable to fossil fuel air pollution (2018). Low, central and high estimates are provided representing a 95% confidence interval.

Southeast Asia	Premature deaths in 2018		
	Low	Central	High
Vietnam	28,000	41,000	58,000
Laos	1,400	2,000	2,900
Thailand	17,000	24,000	34,000
Myanmar	12,000	18,000	24,000
Singapore	890	1,000	2,000
Cambodia	1,900	2,800	4,100
Malaysia	4,300	6,600	10,000
Indonesia	30,000	44,000	61,000
Philippines	11,000	17,000	27,000
Brunei Darussalam	20	30	40
Timor Leste	10	20	30

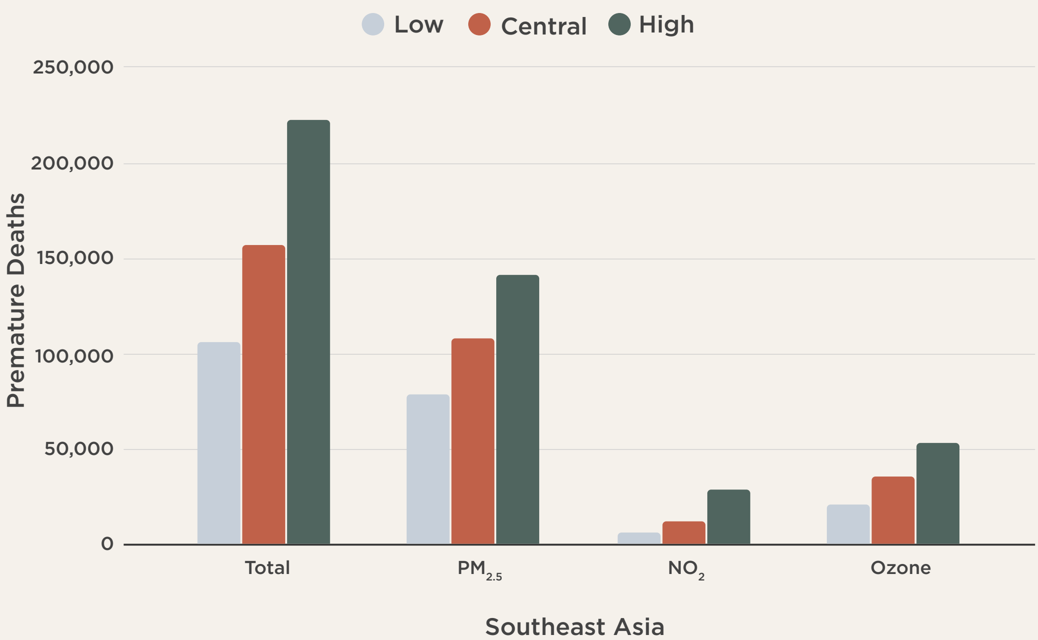

Figure 7: The estimated number of premature deaths in Southeast Asia attributable to fossil fuel air pollution by pollutant (2018). Low, central and high estimates are provided representing a 95% confidence interval.

In Middle Eastern and North African countries, Egypt has the highest estimated number of premature deaths from fossil fuel air pollution (Table 6, Figure 8). Of those, 4,600 (2,300-7800) are related to COPD, 4,000 (1,500-7,000) are related to stroke, and 15,000 (12,000-18,000) are related to ischaemic heart disease and $PM_{2.5}$ exposure attributed to fossil fuel use. The estimated number of annual premature deaths attributable to fossil fuel air pollution for all countries analysed is provided in Appendix 2.

Middle East and North Africa	**Premature deaths in 2018**		
	Low	Central	High
Algeria	2,100	3,000	4,300
Bahrain	200	300	400
Egypt, Arab Rep.	22,000	32,000	51,000
Iraq	2,500	3,500	4,800
Jordan	800	1,200	1,900
Kuwait	290	410	600
Lebanon	1,800	2,700	4,200
Libya	600	900	1,300
Morocco	3,300	5,100	7,500
Oman	140	210	300
Palestine	400	500	700
Qatar	140	230	410
Saudi Arabia	2,200	3,300	5,000
Syrian Arab Republic	3,100	4,700	7,100
Tunisia	1,300	2,100	3,100
United Arab Emirates	900	1,500	2,400
Yemen, Rep.	1,800	3,100	5,200

Table 6: The estimated number of premature deaths in the Middle East and North Africa attributable to fossil fuel air pollution (2018). Low, central and high estimates are provided representing a 95% confidence interval.

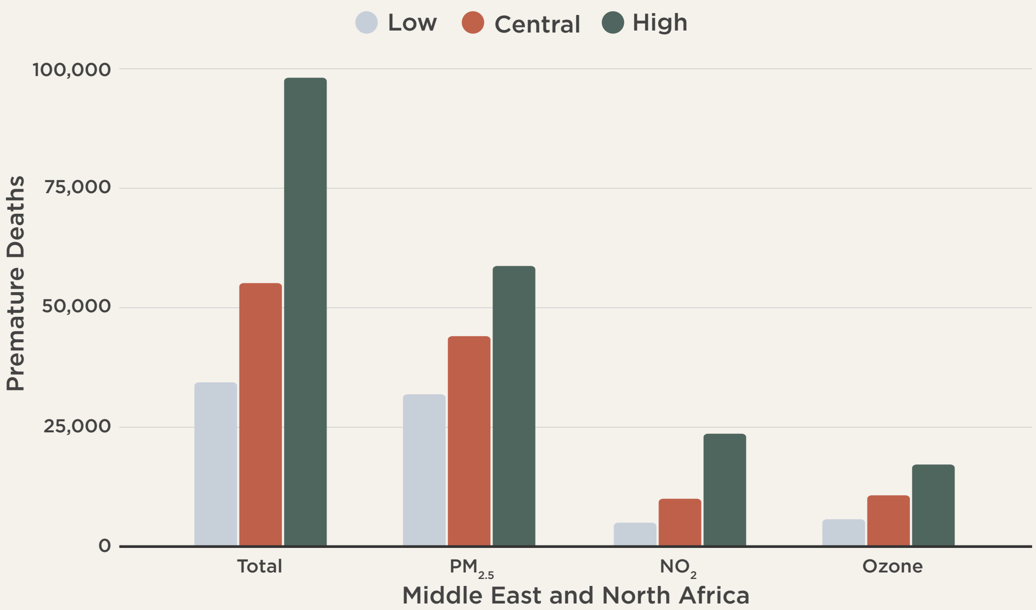

Figure 8: The estimated number of premature deaths in the Middle East and North Africa attributable to fossil fuel air pollution by pollutant (2018). Low, central and high estimates are provided representing a 95% confidence interval.

2.3.2 Economic cost

Population size is a significant driver of the absolute cost of air pollution for society. Also important are factors such as the local availability and cost of healthcare and the rate of infant mortality. Nations that have large populations often have a large absolute cost burden from fossil fuel-related air pollution, and where high air pollution levels intersect with dense populations the impact is magnified.

The cost of fossil fuel air pollution equates to a large percentage of many nations' GDP. The projected cost of fossil fuel air pollution as a percentage of GDP is greatest in China Mainland, where it equates to 6.6% (confidence 4.7-9.0%) of GDP. By comparison, it is 3.4% (2.2-5.1%) and 2.5% (1.8-3.7%) in South Korea and Japan respectively. In Bulgaria, Hungary, Ukraine, Serbia, Belarus, India, Romania and Bangladesh the cost (central estimate) is greater than 5% of GDP. The estimated cost of fossil fuel-related air pollution in Southeast Asia, the Middle East and North Africa is shown in Table 7 and Table 8.

Across East Asia the estimated cost of fossil fuel-related air pollution is high, accounting for more than 2% of GDP across East Asia. Work absences in 2018 from exposure to fossil fuel-related $PM_{2.5}$ are estimated at 748 million (642–853 million) days in China Mainland, costing the economy an estimated US$39 billion (US$33–US$44 billion). In South Korea, Taiwan and Japan the figure is 18 million (16–21 million) days, 5 million (4–6 million) days and 20 million (17–23 million) days, respectively.

In Southeast Asia, the estimated cost of fossil fuel-related air pollution is greater than 2% of GDP in Vietnam, Laos, Thailand and Myanmar (central estimate). Only in Brunei and Timor Leste is the figure less than 1% of GDP (Table 7).

Table 7: The estimated annual cost (% GDP) of fossil fuel-related air pollution in Southeast Asia in 2018. Low, central and high estimates are provided representing a 95% confidence interval.

Southeast Asia	**% GDP total**		
	Low	Central	High
Vietnam	1.8%	2.8%	4.0%
Laos	1.8%	2.9%	4.1%
Thailand	1.4%	2.1%	2.9%
Myanmar	1.8%	2.7%	3.6%
Singapore	0.7%	1.1%	1.8%
Cambodia	1.0%	1.5%	2.1%
Malaysia	0.8%	1.3%	1.9%
Indonesia	0.8%	1.1%	1.6%
Philippines	0.8%	1.2%	1.9%
Brunei Darussalam	0.3%	0.4%	0.6%
Timor Leste	0.1%	0.1%	0.2%

The estimated cost of fossil fuel-related air pollution as a percentage of GDP in the Middle East and North Africa is greatest in Egypt, Lebanon, Bahrain and the UAE (Table 8). Work absences resulting from exposure to fossil fuel-related $PM_{2.5}$ reach 15 million (13–17 million) days in Egypt; 1.3 million (1.1–1.5 million) days in Lebanon; 460,000 (400,000–530,000) days in Bahrain; and 2.7 million (2.3–3.1 million) days in the UAE. The total cost of fossil fuel air pollution for all countries analysed is provided in Appendix 2.

Table 8: The estimated annual cost (% GDP) of fossil fuel-related air pollution in the Middle East and North Africa in 2018. Low, central and high estimates are provided representing a 95% confidence interval.

Middle East and Africa	**% GDP total**		
	Low	Central	High
Algeria	0.3%	0.5%	0.7%
Bahrain	0.9%	1.4%	2.1%
Egypt, Arab Rep.	1.8%	2.8%	4.2%
Iraq	0.5%	0.8%	1.1%
Jordan	0.7%	1.1%	1.5%
Kuwait	0.6%	0.9%	1.2%
Lebanon	1.3%	2.0%	3.0%
Libya	0.6%	0.9%	1.3%
Morocco	0.6%	0.9%	1.4%
Oman	0.3%	0.4%	0.6%
Palestine	0.5%	0.8%	1.0%
Qatar	0.5%	0.8%	1.3%
Saudi Arabia	0.5%	0.7%	1.1%
Syrian Arab Republic	No Data	No Data	No Data
Tunisia	0.6%	1.0%	1.5%
United Arab Emirates	0.8%	1.4%	2.2%
Yemen, Rep.	0.5%	1.0%	1.6%

Solar rooftop at Luang Suan Hospital in Thailand
©Arnaud Vittet/Greenpeace

Salt fields near a wind farm in Guimaras, Philippines
© Veejay Villafranca/Greenpeace

3.0 WHAT CAN BE DONE ABOUT ANTHROPOGENIC AIR POLLUTION?

Realistic scenarios for phasing out fossil fuels are capable of simultaneously reducing air pollution and greenhouse gas emissions[42]. Decarbonising the global economy can bring rapid health gains for society, especially by reducing exposure to air pollutants, most notably $PM_{2.5}$ which has the greatest impact on our health[43].

Solutions to the air pollution crisis, such as emissions controls in Europe, have helped bring about huge reductions in health impacts for citizens. Policy to reduce air pollution does not need to be expensive, and, where interventions are costly to implement, the benefits can outweigh the costs. For example, the United States Clean Air Act has returned substantially greater economic benefits in relation to the costs of implementation, and the benefits exceeded a ratio of 30:1 over the period 1990–2020. Put another way, for every US$1 invested, the US economy saw benefits of at least US$30 returned[44]. Many strategies to control pollution are likely to be cost-effective in cities and countries whatever their level of income[45].

In this section we demonstrate with examples that it is possible and affordable to drastically reduce the health burden of air pollution from fossil fuels, through actions that also support efforts to mitigate anthropogenic climate change. This section focuses on two different fossil fuel burning sectors: transport and oil; and electricity and coal. We demonstrate that action on air pollution is practical, feasible and cost effective.

3.1 Case study one: Switch to sustainable transport

The ways in which humans travel — particularly in highly populated urban areas — must change if we are to tackle the dual threats of air pollution and climate emergency[46,47]. As millions of people take private vehicles on a daily basis for work, school or leisure, neighborhood streets are not only clogged with traffic but diesel and petrol engines contribute to poor air quality and lead to an increased concentration of atmospheric greenhouse gases. It is clear that to reduce harmful levels of particulates and halt global climate heating, a transport revolution is needed, one that ensures a clean, carbon-neutral and universal mobility system for all. Our cities need to support lifestyles that are healthy for residents and for the planet. Low-cost, active and carbon neutral transportation is an important part of this transition, having the combined benefits of reducing urban pollution, greenhouse gas emissions, and rates of cardiovascular disease, cancer, obesity, diabetes, mental illness, and respiratory disease[48]. One of the most important steps governments can take to initiate a move towards a sustainable transport system is to set a phase-out date for diesel and petrol cars, while implementing various urban transport measures, such as restricting cars' access into certain neighborhoods or districts, banning whole categories of cars within city limits, and promoting car-free days. Such initiatives allow residents to imagine what their city could be like without congestion and particulate pollution, with the added benefit of encouraging physical activity. In this case study, we investigate initiatives that national governments have undertaken to improve public health and air quality by removing petrol and diesel cars from city streets.

There are many examples of city authorities that have undertaken initiatives to create cleaner air, for example by promoting pedestrian and cycle-friendly spaces and alternatives to private vehicle transport, such as car clubs or vehicle sharing schemes, and public transport powered by renewable energy. In the UK, Transport for London announced that (correct as of January 2020), four bus routes through the city centre are fully electric[49]. In Shenzhen, all diesel public buses were replaced with electric vehicles in 2018, making it the world's first fully electric fleet[50].

In the United States, New York City's Metropolitan Transportation Authority (MTA) is working towards a zero-emission bus fleet and is in the final stages of a three-year trial of all-electric buses[51]. In 2019, Oslo closed central city streets to privately owned vehicles and cut city centre parking spots[52]. Oslo residents can enjoy a cleaner environment, where walking, cycling, and public transport use is encouraged. Restricting private vehicle use is an effective strategy to reduce fossil fuel use and improve air quality, and in conjunction with alternate and public transport systems, access can be maintained for those unable to walk and cycle[53].

No city has become entirely vehicle free, but car-free days which have operated in cities for many years provide an opportunity to see the potential for health and environmental co-benefits. Car-free events take place in cities around the world, often annually but in some locations, like Bogota, Colombia, roads are closed to cars on a weekly basis[54]. These examples show that, although occasional car-free days are a positive first step, to be effective for human health, car-free events should take place on a regular or continuous basis and attract a high proportion of the community.

As we can learn from the car-free cases, ensuring streets aren't clogged with cars leads to significant health and financial benefits. However, car-free cases are only a partial policy approach to resolve congestion and air pollution in urban areas. The bigger shift is happening globally to move the transport system away from fossil fuels and approach mobility in a way that is sustainable and equitable for all.

More than 15 countries have announced plans to phase out new petrol and diesel cars, and, in some cases, hybrids. Although not perfect, these announcements send a strong signal to markets that there is no future for fossil fuel vehicles. Both to ensure safe air and avoid the worst impacts of climate change, it is necessary to phase out the internal combustion engine and develop alternatives to mass car ownership[55].

It is clear that with technological and social changes, cities can eliminate fossil fuel-powered vehicles, rapidly reduce pollution and help find solutions to climate change. Major cities can pioneer this change, leading the charge toward more sustainable urban spaces that put social equity and justice at the heart of creating a carbon-neutral mobility system for all. In turn this will shape national and global debates on the future of urban transport[56] and empower national governments to set ambitious phase-out dates for petrol and diesel cars while investing in public transport and e-mobility.

On your bike: The benefits of Bogotá's Sunday street closure

One of the longest-running examples of a car-free day event in a city is the Ciclovía in Bogotá, Colombia which was initiated in 1974. The Ciclovía is a weekly event that takes place every Sunday and public holiday in central Bogotá, in which roads are closed to motorised traffic to allow cyclists, skaters and pedestrians traffic-free access to 120 kilometres (74.6 miles) of roads. Similar events take place in more than 15 countries in the Americas and the Caribbean. The aim of the Ciclovía was to encourage more people to take up physical activity, and some people may choose to exercise during Ciclovía precisely because there is no traffic and lower air pollution.[57] The inclusive nature of the Ciclovía boosts its potential to promote activity in children and prevent them from developing obesity.[58]

The cost-benefit ratio in terms of health cost savings of the Bogotá Ciclovía

In terms of health costs savings, the estimated cost–benefit ratio of the Bogotá Ciclovía ranges from US$3.20 to US$4.30 per US$1 invested in the programme.[59] The range reflects uncertainty in the number of adult users, which in a study period between 2005 and 2009, was estimated to be between 516,600 and 1,205,635. A cost–benefit ratio calculated for Medellín, Colombia's second city, which runs a similar Ciclovía programme, found that every US$1 invested yielded a health cost saving of US$1.80. The total benefits of the Ciclovía events however may have been underestimated because only some beneficial factors were included in the analysis. The cost of the Ciclovía programme, based on data collected in the study period in 2005 and 2009, was estimated to be US$6 per capita. For open streets events to be successful, the researchers suggest that the route should pass through different neighbourhoods, be promoted among under-represented ethnic and age groups, and have secure funding to ensure longevity[60].

3.2 Case study two: Generate electricity from renewables, not fossil fuels

Modelling studies suggest that 65% of air pollution related global premature mortality can be attributed to fossil fuel emissions[61]. Replacing fossil fuels with renewable energy from sources such as wind and solar reduces both greenhouse gas emissions and emissions of air pollutants, creating a dual benefit for climate and human health. This transition is both feasible and achievable, and power generated by renewable systems is increasing used globally, as technology has matured and installation costs have fallen drastically.

In the US between 2007 and 2015, the combined contribution from wind and solar to the national grid, as well as from distributed photovoltaic power sources, increased from ~10 GW to ~100 GW[62]. Pollutant emissions avoided by this wind power generation are estimated to have delivered air quality and public health savings of between US$28.4–107.9 billion through the avoidance of an estimated 2,900–12,200 premature deaths, as well as climate benefits savings of US$4.9–98.5 billion. The estimated benefits due to solar power generation were US$1.3–4.9 billion for air quality and public health and US$0.4–8.3 billion for climate benefits, with an avoided 100–500 early deaths.

Air pollution benefits from the closure of coal-fired power stations can exceed the value of the electricity they generated[63]. As we adopt renewable power and phase out fossil fuels, large health benefits can be realised by prioritising infrastructure with the greatest potential to reduce exposure to air pollutants. Power generation from coal, oil and gas contribute to air pollution and the climate crisis. Phasing out these technologies promises environmental and health benefits. The benefits of a fossil fuel phaseout can be most significant for coal power stations because of the higher SO_2, NOx, and $PM_{2.5}$ emission rates associated with coal[64]. Emission standards and plant closures in the United States power generation industry drove emission reductions of 20%, 72%, 50% and 46% for CO_2, SO_2, NOx and $PM_{2.5}$ respectively between 2007 and 2015.

A breath of fresh air: The benefits of phasing out coal-fired power plants

The closure of existing coal-fired power plants is beneficial to the environment and human health. Air quality studies show that the closure of coal-fired power plants brings health benefits to people living and working in their vicinity.

- One study that evaluated the impact of coal-fired power plants on childhood development[65] followed two groups of non-smoking pregnant women living within 2.5 kilometers of the Tongliang power station in Chongqing, China. The first group (n=150) was enrolled in 2002 and had been exposed to polyaromatic hydrocarbons from a power plant; the second group (n=158) were enrolled in 2005 and had not been exposed to the same source because the plant closed in 2004. Exposure to PAHs has been linked to developmental problems, particularly in unborn and young children. The coal power plant which operated between December and May until 2004 did not use modern pollution reduction technology. The study found that reduced exposure to PAH in the second group was associated with beneficial effects on neurodevelopment as well as molecular changes related to improved brain development and health. The researchers recommend reducing exposure to toxic pollutants to help enhance neurodevelopment.
- Monitoring[66] that took place from 2011 to 2014 in Pittsburgh, Pennsylvania, United States, found that, following the closure of three coal-fired power plants, there was a downward trend in ambient $PM_{2.5}$ levels. The researchers used $PM_{2.5}$ measurements from 12 ground stations and from satellites to monitor the aerosol optical depth (AOD), observing a decline in AOD over the study period.
- A well-documented case study[67] in Dublin, Ireland, describes how a 1990 ban on bituminous coal sales reduced wintertime black smoke by 70% and decreased deaths from respiratory illness by 15% (about 116 people per year).

Air pollution protest in Bangkok
©Wason Wanichakorn/Greenpeace

Toxic smog in Bangkok
©Chanklang Kanthong/Greenpeace

4.0 CONCLUSIONS

4.1 Costs

We estimate that air pollution resulting from fossil fuels causes approximately 4.5 million premature deaths each year globally. Air pollution from fossil fuels costs us an estimated 1.8 billion lost working days worldwide per year through poor health. This hits our economy and seriously damages people's well-being. Combining health costs and work absences, an economic cost equivalent to 3.3% of global gross domestic product, or US$8 billion per day, is estimated to arise from fossil fuel-related air pollution, according to this study.

The air pollution health crisis is driven by burning fossil fuels, which – because burning coal, gas and oil emits greenhouse gases – also contributes to the climate emergency. Governments making investments to replace fossil fuels with clean renewable energy stand to benefit from long-term economic returns and to deliver improved health and wellbeing to their citizens.

The need to move away from reliance on fossil fuels is clear and, while the cost of our reliance on coal, oil and gas continues to soar, life-saving alternatives are increasingly widespread and affordable.

4.2 Transport

Car-free initiatives have demonstrated that radical changes to our transport systems have the potential to boost physical activity, reduce emissions of harmful air pollutants and greenhouse gases and improve health. The money saved through these health benefits has been demonstrated to return multiple times the cost of implementation. It also shows the extent to which fossil fuel companies are currently profiting at the expense of our communities, who pay the price for air pollution. Investment in alternative sustainable alternative transport systems can be financially sound and positive for health, wellbeing and the planet.

Our transport systems urgently need to be reorganised so that they use energy and resources efficiently and operate without either directly or indirectly emitting harmful pollutants. Our cities need fewer and cleaner vehicles operating alongside greater use of public transport and widespread investments in shared mobility, walking and cycling. To achieve this, national governments must implement ambitious phase-out dates for diesel and petrol cars while investing in sustainable transport and enabling low-carbon alternatives, such as walking or cycling. Pioneering cities and regions can lead the way, helping to shape national and global debates on the future of urban transport.

4.3 Energy

A phaseout of existing fossil fuel power plants and an end to the construction of new projects is essential to limit global warming to 1.5 °C above pre-industrial levels, but it will also reduce the emission of air pollutants that today disperse over hundreds of kilometers.

Emissions from coal combustion have been linked to a broad range of illnesses, including developmental problems in children and premature deaths from respiratory illnesses. Deployment of renewable technology in the electricity grid in parts of the US has reduced reliance on fossil fuels and reduced the emission of pollutants. The removal of fossil fuels is helping to prevent premature deaths and bring vast savings in health costs.

Economic savings from the improved air quality resulting from coal-fired power station closures can exceed the value of the electricity they generated[68]. Moving our energy generation sector from fossil fuels to renewables is an essential step towards preventing catastrophic climate change and protecting our health. A just transition to renewable energy is feasible, and we can't afford to wait any longer. Cities, governments and companies need to take action now.

GLOSSARY

Air pollutant	An unwanted substance found in the air in the form of a solid particle, a liquid droplet or a gas. The substance may be harmful to human health, or damaging to the environment.
ALRI	Acute lower respiratory illness.
AOD	Aerosol optical depth. Aerosols are solid particles in the atmosphere that may be of different sizes and from natural or anthropogenic sources. Aerosols can have different effects depending on what they are made from and the geographical location. Measuring aerosol optical depth can indicate the quantity of aerosol depending upon how much light passes through.
Central estimate	See: Confidence interval.
CEV	Cerebrovascular disease.
Confidence interval	Scientific studies that use computer models do not give results with absolute certainty. Instead a range is provided (known as an 'interval'). The 'confidence range' is the range that is most likely to contain the true value. A 95% confidence interval means that with 95% probability, reality is somewhere inside the confidence interval, and a 5% chance it is outside the interval (either higher or lower than the range of numbers in the range). The value with 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 the low and the high estimate.
COPD	Chronic obstructive pulmonary disease.
DEFRA	The Department for Environment, Farming and Rural Affairs of the government of the United Kingdom.
Dust	Solid airborne particles. A subclass of dust is $PM_{2.5}$.
GDP	Gross domestic product.
GNI	Gross national income.
High estimate	See: Confidence interval.
IHD	Ischaemic heart disease.
Low estimate	See: Confidence interval.
MODIS	Moderate resolution imaging spectroradiometer.
NO_2	Nitrogen dioxide.
NOx	Nitrogen oxides. A generic term for NO and NO_2, a group of trace gases that are harmful to human health.
O_3	Ozone.

$PM_{2.5}$	Fine particulate matter.
ppb	Parts per billion. The number of units of mass of a contaminant per 1000 million units of total mass.
PPP	Purchasing power parity is a currency exchange rate used to determine the value of an international dollar such that it has the same purchasing power over gross national income as a United States dollar has in the United States.
SO_2	Sulfur dioxide.
WHO	World Health Organization
$\mu g/m^3$	Microgram per cubic meter. The mass of a substance in milligrams, in one cubic metre of a gas.

APPENDIX 1: METHODOLOGY

This paper presents the first global estimate of the economic burden caused by air pollution from fossil fuels. We use global datasets describing surface level concentrations of $PM_{2.5}$, ozone and NO_2 to perform a health impacts assessment and subsequent cost calculation. The health impacts are determined by combining pollutant concentration maps with population data, country or region-level health statistics and pollution exposure response functions for the year 2018. The complete methodology is presented below.

Exposure to air pollution from fossil fuels

The concentrations of $PM_{2.5}$ and ozone linked to fossil fuel emissions have previously been estimated globally for 2015[69], and total NO_2 pollution levels for the year 2011 have been mapped at high resolution[70]. As NOx emissions sources are heavily dominated by fossil fuel burning, we assume that NO_2 concentrations above the thresholds described in Table A1 represent NO_2 resulting from fossil fuel use. For example, for deaths linked to NO_2 exposure, the threshold is a concentration 20 μm/m^3 to link those deaths to fossil fuels. This assumption can be considered conservative because NOx emissions are heavily dominated by fossil fuels globally, particularly in cities where the majority of harmful exposure takes place.

The surface $PM_{2.5}$ and NO_2 data then are scaled to represent concentrations in 2018. The scaling is completed using satellite based observations of the respective years using MODIS and OMI data products. NASA MODIS (Moderate Resolution Imaging Spectroradiometer) is an Earth observation instrument that is carried on two NASA satellites, Terra and Aqua. It monitors aerosols in the atmosphere and completes a scan of the globe every 1-2 days[71]. OMI (Ozone Monitoring Instrument) monitors pollutants including NO_2 from the NASA AURA satellite. These satellite-based measurements quantify the total atmospheric amount of each pollutant, rather than surface concentrations, and are only used to adjust the surface level maps. Ozone is not adjusted from 2015 levels.

To calculate pollutant exposure, ozone and the adjusted 2018 $PM_{2.5}$ and NO_2 data are combined with population and health datasets updated to the latest available data (2017-2018)[72,73,74,75].

Health impacts and costs

We use the adjusted 2018 $PM_{2.5}$, ozone and NO_2 data and concentration-response functions to determine the incidence of health impacts for a given population[76]. A concentration response function relates a pollutant concentration to the response or impact of that pollutant on a population. Deaths, years of life lost and years lived with disability due to $PM_{2.5}$ exposure are calculated using non-linear, age-specific risk derived by Burnett et al[77] and Global Burden of Disease, which give the increase in risk of different health effects as a function of pollutant concentration, compared with clean air. Other health impacts are projected using log-linear risk functions that are expressed as increase in relative risk per 10μm/m^3, or 10 ppb increase in pollutant concentration, and an assumed no-risk threshold, usually based on lowest concentration in study datasets that detected health risks. The following health impacts are considered:

Deaths of small children from lower respiratory infections

This health impact is assessed using the $PM_{2.5}$ concentration results from Lelieveld et al (2019) and the Global Burden of Disease risk function for lower respiratory diseases[78].

The economic losses from these air pollution-related deaths are assessed based on the resulting reduction in life expectancy, with one year of life lost equating to economic losses of EUR56,000 in the European Union, following the EEA cost-benefit methodology[79], and adjusted by GNI PPP by country or region, with an elasticity of 0.9 as recommended by OECD[80].

Diabetes, asthma and other chronic respiratory diseases, and disabilities caused by stroke

The Global Burden of Disease project[81] has quantified the degree of disability caused by each disease into a "disability weight" that can be used to compare the costs of different illnesses.

The economic cost of disability and reduced quality of life caused by diabetes and chronic bronchitis is assessed based on these disability weights, combined with the economic valuation of disability used by the UK environmental regulator DEFRA[82]. The valuation is adjusted by GNI PPP for other countries. For example, type 2 diabetes without complications has a disability weight of 4.9%, meaning that the cost of one year lived with diabetes is estimated at 4.9% of the cost of one year lived with disability, or US$4000 in the UK and US$1600 at world average income level.

The economic cost of asthma related to fossil fuel pollution is assessed based on two indicators: new cases of asthma linked to NO_2 exposure, and emergency room visits related to $PM_{2.5}$ and ozone exposure. An assessment of the direct and indirect cost per year associated with childhood asthma, including medical costs and loss of income to the child's caregiver, found a cost of US$3,800 and US$4,000 in two different communities in California, US[83]. The midpoint of these two valuations is used for the estimates, adjusted by the ratio of California's Gross Regional Product to US national average, and by GNI PPP for other countries. The cost of an emergency room visit is taken from the same study.

Exposure to $PM_{2.5}$ is very likely linked to an even larger number of new asthma cases globally than exposure to NO_2, but uncertainty in the estimates is large[84], so this effect is not included. Instead, we include the economic cost of emergency room visits for asthma linked to $PM_{2.5}$ and ozone exposure, which is only a small part of the overall cost of the burden of asthma linked to $PM_{2.5}$.

Preterm Birth

$PM_{2.5}$ exposure to pregnant women increases the likelihood of preterm birth and low birth weight, which in turn increases the risk of many health and development issues throughout a baby's life. Approximately 2 million preterm births per year can be attributed to the exposure of pregnant women to $PM_{2.5}$ pollution from fossil fuels specifically, based on CREA analysis using the Lelieveld et al (2019) concentration results and the concentration-response relationship established by Trasande et al[85]. The same study estimated the economic costs of a preterm birth, primarily lower economic productivity and increased health care costs, at US$300,000 per birth in the US. This concentration-response function and cost estimate is used in the analysis; the valuations are adjusted using GDP PPP within regional groups.

Work Absence

Exposure to $PM_{2.5}$ air pollution from fossil fuels leads to increased work absences due to illness (sick leave). We estimate the incidence of work absences using WHO recommended concentration response functions[86]. The economic cost of these sick leaves is evaluated at EUR130 per day in the European Union, based on EEA recommendations[87], and adjusted for other countries based on GDP PPP.

Table A1. Concentration Response Functions*

Concentration Response Functions							
Health effect	**Exposure**	**Risk ratio**	**Concentration change**	**No-risk threshold**	**Unit**	**Reference**	**Incidence data**
Asthma emergency room visits, children	$PM_{2.5}$	1.025 (1.013, 1.037)	10	6	µg/m³	Zheng 2015	Anenberg et al 2018
Asthma emergency room visits, children	O_3	1.018 (1.01, 1.024)	10	2	ppb	Zheng 2015	Anenberg et al 2018
Asthma emergency room visits, adults	$PM_{2.5}$	1.023 (1.015, 1.031)	10	6	µg/m³	Zheng 2015	Anenberg et al 2018
Asthma emergency room visits, adults	O_3	1.018 (1.012, 1.022)	10	2	ppb	Zheng 2015	Anenberg et al 2018
Preterm births	$PM_{2.5}$	1.15 (1.07, 1.16)	10	8.8	µg/m³	Trasande et al 2016	Chawanpai-boon et al 2019
Deaths, chronic obstructive pulmonary disease	O_3	1.12 (1.08, 1.16)	10	35	ppb	Malley et al 2017	GBD 2017
Deaths, non-communicable diseases and lower respiratory infections, adults	NO_2	1.037 (1.021, 1.080)	10	20	µg/m³	WHO HRAPIE 2013	GBD 2017
Years of life lost, non-communicable diseases and lower respiratory infections, adults	NO_2	1.037 (1.021, 1.080)	10	20	µg/m³	WHO HRAPIE 2013	GBD 2017
Work absences, days	$PM_{2.5}$	1.046 (1.039, 1.053)	10	0	µg/m³	WHO HRAPIE 2013	EEA 2014
New cases of asthma in children	NO_2	1.26 (1.10, 1.37)	10	2	ppb	Achakulwisut et al 2019	GBD 2017

*Table references[88,89,90,91,92,93,94,95,96,97,98]

APPENDIX 2: SUMMARY OF COST AND MORTALITY DATA

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Afghanistan	170	270	380	2,600	3,900	5,900
Albania	260	400	590	1,000	1,500	2,200
Algeria	530	840	1,100	2,100	3,000	4,300
American Samoa	No Data	No Data	No Data	0	0	1
Andorra	No Data	No Data	No Data	20	30	50
Angola	98	170	270	250	410	700
Antigua and Barbuda	3	5	7	4	6	7
Argentina	2,600	4,400	7,900	5,300	8,600	15,000
Armenia	270	370	480	1,300	1,700	2,200
Australia	3,900	6,100	8,900	2,000	2,900	4,200
Austria	11,000	15,000	21,000	5,800	7,900	11,000
Azerbaijan	460	680	960	1,600	2,200	3,200
Bahamas, The	86	130	170	40	60	80
Bahrain	330	510	750	200	300	400
Bangladesh	9,100	14,000	18,000	67,000	96,000	130,000
Barbados	12	18	25	10	20	30
Belarus	2,400	3,200	4,400	7,800	10,000	14,000
Belgium	8,500	12,000	18,000	5,000	6,800	9,500
Belize	7	11	15	20	30	40
Benin	24	39	55	220	350	520
Bermuda	29	44	59	9	10	20
Bhutan	31	54	79	150	240	350
Bolivia	28	59	100	130	250	450
Bosnia and Herzegovina	680	950	1,200	2,300	3,100	3,900
Botswana	57	91	140	100	150	200
Brazil	9,800	14,000	22,000	20,000	28,000	43,000

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Brunei Darussalam	35	53	76	20	30	40
Bulgaria	2,900	3,900	5,200	6,800	9,000	12,000
Burkina Faso	59	95	130	600	900	1,300
Burundi	7	11	17	200	320	500
Cabo Verde	6	9	13	30	40	50
Cambodia	240	360	520	1,900	2,800	4,100
Cameroon	99	160	230	570	900	1,000
Canada	25,000	38,000	57,000	15,000	21,000	30,000
Central African Republic	11	18	27	160	260	400
Chad	61	99	140	550	850	1,000
Chile	1,600	2,600	4,500	2,300	3,800	6,600
China Mainland	650,000	900,000	1,200,000	1,300,000	1,800,000	2,500,000
Colombia	1,500	2,400	3,600	4,800	6,900	9,800
Comoros	1	2	3	9	10	19
Congo, Dem. Rep.	79	130	210	1,100	2,000	3,300
Congo, Rep.	9	15	22	44	70	100
Costa Rica	230	340	450	380	530	710
Côte d'Ivoire	16	38	66	90	200	400
Croatia	2,000	2,800	3,700	3,300	4,400	5,700
Cuba	No Data	No Data	No Data	2,000	2,800	3,800
Cyprus	380	570	790	310	440	630
Czech Republic	7,700	11,000	15,000	8,000	11,000	14,000
Denmark	4,600	6,700	9,500	2,000	2,800	3,800
Djibouti	No Data	No Data	No Data	40	80	100
Dominica	2	3	4	5	7	9
Dominican Republic	310	490	700	600	1,000	1,400
Ecuador	670	1,000	1,500	2,000	2,700	3,700

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Egypt, Arab Rep.	4,400	6,900	10,000	22,000	32,000	51,000
El Salvador	160	260	370	697	1,100	1,500
Equatorial Guinea	3	7	12	4	9	20
Eritrea	39	66	98	390	640	970
Estonia	430	650	900	460	630	820
Eswatini	41	66	97	120	180	270
Ethiopia	240	370	480	2,600	3,900	5,400
Fiji	8	12	17	20	20	30
Finland	2,800	4,300	5,800	1,600	2,100	2,700
France	37,000	54,000	79,000	27,000	37,000	55,000
Gabon	5	9	13	8	10	20
Gambia, The	4	8	11	60	100	150
Georgia	510	700	890	2,200	2,900	3,600
Germany	94,000	140,000	210,000	57,000	81,000	120,000
Ghana	38	73	120	200	370	600
Greece	4,200	6,100	8,700	6,000	8,400	12,000
Greenland	No Data	No Data	No Data	8	10	20
Grenada	3	4	6	6	8	10
Guam	No Data	No Data	No Data	10	16	22
Guatemala	390	620	870	1,200	1,700	2,400
Guinea	27	43	60	270	410	590
Guinea Bissau	3	6	8	40	60	90
Guyana	6	9	12	20	20	30
Haiti	61	100	150	772	1,300	1,900
Honduras	100	170	260	600	980	2,000
Hungary	6,700	9,400	13,000	9,400	13,000	17,000
Iceland	76	110	150	30	40	50
India	100,000	150,000	190,000	715,000	1,000,000	1,300,000

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Indonesia	7,600	11,000	16,000	30,000	44,000	61,000
Iran, Islamic Rep.	3,800	5,300	7,300	13,000	17,000	24,000
Iraq	1,400	2,100	2,800	2,500	3,500	4,800
Ireland	2,500	3,800	5,000	900	1,200	1,600
Israel	3,000	4,500	6,200	1,800	2,500	3,600
Italy	41,000	61,000	91,000	39,000	56,000	83,000
Jamaica	90	140	200	310	460	640
Japan	88,000	130,000	180,000	75,000	100,000	150,000
Jordan	300	490	700	800	1,200	1,900
Kazakhstan	2,000	2,800	3,900	3,500	4,800	6,400
Kenya	190	290	380	1,100	1,600	2,300
Kiribati	0	0	0	0	0	0
Korea, Dem. People's Rep.	No Data	No Data	No Data	24,000	38,000	56,000
Korea, Rep.	37,000	56,000	85,000	28,000	40,000	61,000
Kosovo	180	270	380	800	1,200	1,700
Kuwait	840	1,300	1,700	290	410	600
Kyrgyz Republic	77	110	150	800	1,100	1,600
Lao PDR	320	510	720	1,400	2,000	2,900
Latvia	850	1,200	1,700	1,100	1,500	2,100
Lebanon	890	1,400	2,100	1,800	2,700	4,200
Lesotho	39	67	100	370	590	870
Liberia	2	3	4	20	40	60
Libya	300	470	660	600	900	1,300
Lithuania	1,700	2,300	3,000	2,000	2,600	3,300
Luxembourg	1,000	1,500	2,300	250	350	500
Madagascar	11	19	29	180	300	450
Malawi	6	11	16	170	280	410
Malaysia	2,800	4,500	6,700	4,300	6,600	10,000

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Maldives	17	26	38	30	40	60
Mali	58	99	140	500	800	1,300
Malta	140	200	260	120	170	220
Marshall Islands	0	1	1	1	2	3
Mauritania	11	20	28	100	170	250
Mauritius	23	33	44	30	50	60
Mexico	20,000	29,000	41,000	37,000	51,000	73,000
Micronesia, Fed. Sts.	1	2	3	4	6	9
Moldova	450	600	750	2,300	3,000	3,600
Mongolia	130	200	270	410	570	780
Montenegro	150	210	280	370	480	620
Morocco	670	1,100	1,600	3,300	5,100	7,500
Mozambique	12	20	30	200	340	530
Myanmar	1,300	1,900	2,500	12,000	18,000	24,000
Namibia	15	26	39	36	56	84
Nepal	580	940	1,400	7,800	12,000	18,000
Netherlands	14,000	21,000	30,000	7,200	9,900	14,000
New Zealand	190	270	350	110	140	170
Nicaragua	38	60	83	300	440	600
Niger	35	60	89	530	880	1,000
Nigeria	1,300	2,200	3,200	4,600	7,600	13,000
North Macedonia	390	540	700	1,200	1,600	2,000
Northern Mariana Islands	No Data	No Data	No Data	3	4	6
Norway	4,300	6,000	8,500	1,500	2,100	2,800
Oman	200	320	430	140	210	300
Pakistan	3,800	6,100	9,200	32,000	50,000	76,000
Palestine	82	120	160	400	500	700

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Panama	170	260	360	230	310	410
Papua New Guinea	75	120	200	290	430	620
Paraguay	85	140	210	250	380	540
Peru	550	970	1,700	1,500	2,500	4,600
Philippines	2,500	4,000	6,000	11,000	17,000	27,000
Poland	21,000	29,000	38,000	30,000	39,000	51,000
Portugal	2,700	4,100	6,300	3,300	4,800	7,200
Puerto Rico	470	730	1,000	420	610	860
Qatar	1,000	1,600	2,400	140	230	410
Romania	9,100	13,000	17,000	17,000	22,000	29,000
Russian Federation	50,000	68,000	97,000	89,000	120,000	160,000
Rwanda	18	30	45	240	390	590
Samoa	0	0	1	1	1	2
São Tomé and Principe	1	1	2	4	7	10
Saudi Arabia	3,800	6,000	8,800	2,200	3,300	5,000
Senegal	70	120	160	480	740	1,100
Serbia	2,600	3,700	4,900	8,500	11,000	15,000
Seychelles	6	8	11	6	9	11
Sierra Leone	8	13	18	120	190	280
Singapore	2,500	4,000	6,500	890	1,000	2,000
Slovak Republic	3,700	5,100	6,700	4,100	5,400	7,000
Slovenia	1,300	1,800	2,500	1,300	1,700	2,300
Solomon Islands	2	4	6	10	20	20
Somalia	No Data	No Data	No Data	610	1,000	2,000
South Africa	4,300	6,300	8,200	9,700	13,000	16,000
South Sudan	53	87	130	290	480	750
Spain	16,000	24,000	36,000	17,000	25,000	37,000

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	**Estimated total cost (Million USD)**			**Estimated total premature deaths (2018)**		
	Low	**Central**	**High**	**Low**	**Central**	**High**
Sri Lanka	460	760	1,100	2,100	3,300	4,800
St. Lucia	5	8	11	10	10	20
St. Vincent and the Grenadines	2	3	4	5	7	10
Sudan	180	320	460	1,900	3,100	4,600
Suriname	5	8	11	10	20	30
Sweden	5,400	7,800	11,000	3,000	4,000	5,200
Switzerland	11,000	16,000	23,000	4,100	5,500	7,600
Syrian Arab Republic	No Data	No Data	No Data	3,100	4,700	7,100
Taiwan	11,000	16,000	23,000	12,000	16,000	24,000
Tajikistan	65	96	130	770	1,000	2,000
Tanzania	76	130	180	700	1,000	1,500
Thailand	7,000	11,000	15,000	17,000	24,000	34,000
Timor-Leste	1	3	5	10	20	30
Togo	11	18	26	100	200	300
Tonga	0	1	1	1	1	2
Trinidad and Tobago	41	67	100	40	70	100
Tunisia	240	400	590	1,300	2,100	3,100
Turkey	14,000	21,000	30,000	28,000	40,000	58,000
Turkmenistan	240	360	520	500	700	1,000
Uganda	36	57	79	500	700	1,100
Ukraine	6,000	8,000	10,000	35,000	45,000	57,000
United Arab Emirates	3,500	5,900	9,400	900	1,500	2,400
United Kingdom	46,000	66,000	98,000	30,000	41,000	62,000
United States	430,000	610,000	870,000	170,000	230,000	310,000
Uruguay	280	450	730	800	630	1,000
Uzbekistan	410	590	810	3,400	4,800	6,600

Impact attributed to fossil fuel-related air pollution by country/region						
Country/Region	Estimated total cost (Million USD)			Estimated total premature deaths (2018)		
	Low	Central	High	Low	Central	High
Vanuatu	1	2	3	5	7	11
Venezuela, RB	1,800	2,800	4,200	1,900	2,900	4,200
Vietnam	4,500	6,800	9,800	28,000	41,000	58,000
Virgin Islands (U.S.)	No Data	No Data	No Data	10	20	20
Yemen, Rep.	150	280	450	1,800	3,100	5,200
Zambia	33	56	80	200	300	500
Zimbabwe	56	91	130	200	300	500

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