HIDDEN COSTS:

POLLUTION FROM COAL POWER FINANCED BY OECD COUNTRIES

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Cover image: A man and child stay warm next to small piles of burning coal illegally scavenged near an open-cast mine in the Jharia district of the eastern Indian state of Jharkhand.
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EXECUTIVE SUMMARY

In order to stay within the carbon budget necessary to keep global warming to below 2°C, at least three quarters of fossil fuel reserves globally will need to stay in the ground. As coal makes up two-thirds of the carbon content of known global fossil fuel reserves, coal poses a serious threat to the climate. Despite this, international public finance for coal use remains significant. Coal support provided by the Organisation for Economic Co-operation and Development (OECD) country official Export Credit Agencies (ECA) totaled $34 billion between 2007 and 2014.

In this paper, we analyze some of the economic costs of 20 OECD country ECA-financed coal power plants, from both local air pollution and global climate change impacts. These power plants were identified to be operational as of 2015 in 8 countries (Chile, India, Indonesia, Mexico, Morocco, Philippines, Turkey, and Vietnam).

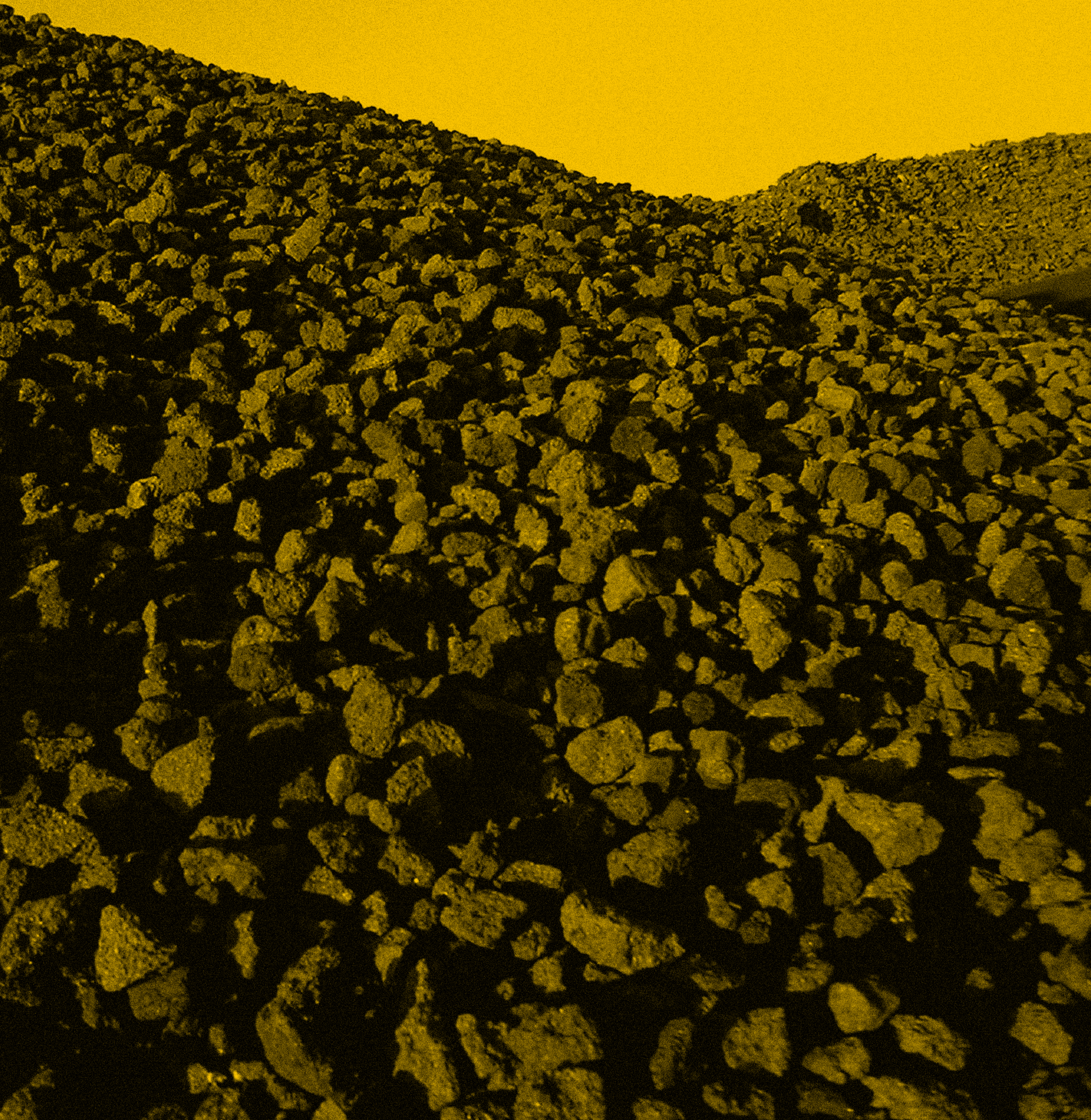
The economic costs of emissions associated with these 20 projects are estimated to be in the range of $7.7 to $32.1 billion in 2015 (in 2015 dollars). The annual costs of local air pollution are estimated to be $3.6 billion under a lower scenario (assuming country-specific pollution controls) and $20.2 billion under a higher scenario (assuming no pollution controls). These costs accrue to the local populations in the countries with the coal-fired plants. The costs of emissions contributing to global climate change are estimated to be $4.1 billion under a lower scenario ($36/t$CO_2$e) and $12.0 billion under a higher scenario ($105/ t$CO_2$e).

The high end of the total economic costs far exceeds the total OECD ECA investment in these 20 plants of $8.6 billion. To get a sense of the magnitude of local air pollution costs, on average $1 in OECD country ECA investment in these projects generated external local air pollution costs of $0.40 to $2.40 in 2015. This represents a single year's worth of costs from local air pollution in projects with lifetimes that can reach 50 years.

The majority of OECD country ECA coal finance for the plants identified was delivered by Japan (58%), followed by Korea (23%) and the United States (11%). Korea has the highest associated costs of emissions from the OECD country ECA-financed coal plants, followed by Japan and the United States.

Because most of the OECD country ECA-financed coal-fired power capacity considered in this study is located in India, India is estimated to experience at least 76% of the total ECA-associated local air pollution costs. Internalizing the total external costs would increase the costs of power generation by an estimated $0.05/kWh - $0.27/kWh across the 8 countries, making renewable energy, such as solar photovoltaics and onshore wind, even more cost-competitive with coal in these countries.

INTRODUCTION



The Intergovernmental Panel on Climate Change (IPCC) has concluded that greenhouse gases (GHGs) need to stabilize at atmospheric concentration levels of about 450 ppm CO_2e by 2100 in order to make it likely (at least a 66% chance) that global warming remains below 2°C. Limiting likely warming to this level will require that total carbon emissions to not rise above 2,900 $GtCO_2e$ over preindustrial levels; about 1,900 $GtCO_2e$ has been emitted by 2011, leaving a remaining budget of just 1,000$GtCO_2e$.[1] However, the combustion of the currently economically recoverable fossil fuel reserves would result in 3,260 $GtCO_2e$ of emissions. Analysis suggests that at least three quarters of proven fossil fuel reserves - and over 80% of coal reserves - must stay in the ground to stay below 2°C and maximize social welfare.[2, 3]

Further, fossil fuels have additional local social costs – in particular the local health costs of air pollution.

The full social costs of fossil fuel combustion are not reflected in the price of fossil fuels, resulting in a massive market failure.[6] The main negative externalities of fossil fuel combustion include:

- the health costs of local air pollution from particulate matter with a diameter up to 2.5 micrometers (PM 2.5), sulfur dioxide (SO_2), and nitrogen oxides (NOx), and
- the global climate change costs due to CO_2 emissions.[7]

The International Monetary Fund (IMF) estimates that the global air pollution and climate change externalities associated with coal combustion were on the order of $3,123 billion in 2014 (net of any fuel taxes).[7] Of course, the two externalities are inter-linked: climate change mitigation efforts, such as a shift to low-carbon electricity generation, will have large positive health impacts.[8]

Despite the need to phase out coal use for electricity generation in order to stay below 2°C and in spite of the known local health impacts of coal combustion, international public finance for coal use remains significant. Between 2007 and 2014, more than $73 billion was approved for coal; of this, 77% was directed to coal-fired power plants. Coal support provided by the Organisation for Economic Co-operation and Development (OECD) country official Export Credit Agencies (ECA) was $34 billion over this period, almost half of the total (47%). Japan alone was responsible for 26% of the total international support for coal, and the two Japanese ECAs – Japan Bank for International Cooperation and Nippon Export and Investment Insurance – provided 49% of the total ECA finance for coal.[4]

Over the 2007 to 2014 period, total international public finance for coal has decreased, although not for OECD country ECAs. Over time as multilateral development banks have shifted dramatically away from coal finance, OECD country ECAs have comprised a greater share of international public finance for coal (Box 1).[4] With regard to total OECD country ECA support for electric power generation, the OECD reports that finance for non-hydro renewable energy from 2003 to 2013 was about one third that for fossil fuel-fired power plants[5], but the OECD data may not comprehensive. Bast et al.[4] found that OECD official data on total coal finance only covered 41% of the total OECD country ECA finance for coal.

ECAs support export transactions originating from corporations (or in some cases, investors) from their home country, providing financial support to export-oriented business, and they may also extend credits to importers to attract investment in their home country. Export credits vary in duration, typically from two to ten years. OECD ECAs generally provide government-backed loans, as well as risk guarantees and insurance to cover the overall risk of an investment (e.g. currency transfer, political risk and conflict, breach of contract) at a lower cost and longer tenor than commercially-available loans and insurance. By providing preferential financing terms, and mitigating major project risks, ECAs remove key obstacles for large-scale coal projects.

The goal of this paper is to analyze the economic costs – both from local air pollution and global climate change impacts – for OECD country ECA-financed coal power plants in 2015.

This analysis illuminates costs that may push projects beyond their economic viability compared to other less pollution-intensive forms of electricity generation. Our focus is on coal, given the current momentum in establishing limits to finance for coal-fired power generation (see Box 1), because of the particularly significant externalities associated with coal combustion, and because there is greater availability of data on the OECD ECA finance for coal projects.

Box 1. Multilateral development banks, bilateral development finance institutions, and some export credit agencies have shifted away from **coal finance**

Public finance institutions often provide support to coal mining and coal-fired power at highly preferential terms, and support averaged more than $9 billion per year between 2007 and 2014.[4] While this finance continues at a significant level, a number of governments and public finance institutions have recently established limits on finance for coal-fired power projects. The United States was the first to move in 2013, when the US Treasury Department announced guidelines that greatly restricted international coal finance from US public finance institutions.[9] These guidelines affected US participation in multilateral development banks, and eventually included the Overseas Private Investment Corporation (OPIC) and the US Export-Import Bank (ExIm). In 2013 the World Bank, European Investment Bank, and European Bank for Reconstruction and Development all announced curbs on coal finance. In 2014, Germany announced some partial restrictions on coal finance, and French President Francois Hollande announced that France would end export credits for most coal-fired power projects.[3]

Also in 2014, the Netherlands, the United Kingdom and the United States tabled a proposal that would limit OECD export credit agency support for coal. In these discussions, Japan (the world's largest provider of public finance for coal between 2007 and 2014), Korea, and Australia have resisted limits on export credits for coal from the OECD countries.[10] However, recent developments may change the tone of the forthcoming OECD discussions in November 2015. In September this year, the US and China released a joint presidential statement on climate change.[11] In this statement, China pledged to strengthen its own regulations "with a view to strictly controlling public investment flowing into projects with high pollution and carbon emissions both domestically and internationally."

These recent developments reflect a growing tide of institutions and governments placing restrictions on international public finance for coal-fired power projects.

METHODOLOGY

The starting point for the analysis of the economic costs of OECD country ECA-financed coal power plants is a database on international coal finance compiled by the Natural Resources Defense Council, Oil Change International and World Wide Fund for Nature (NRDC-OCI-WWF).[12] The database includes information on public finance (direct loans, guarantees, policy lending, and technical assistance) for coal (power plants, coal power emissions controls, coal mining, transmission and distribution linked directly to coal-fired power plants, and other coal-related finance) from institutions based in OECD countries, China, and Russia from 2007 to 2014. It includes finance from multilateral development banks, ECAs in OECD countries and China, development agencies and banks, and majority state-owned banks.

For this paper, we are considering only coal power plants financed by OECD-country ECAs that were operational by 2015. Power plants were excluded if the operational date was not clear, or if there were missing data on installed capacity, yielding 20 power plants in 8 countries (Appendix I). It is likely that a number of coal power plants financed by OECD-country ECAs between 2007 and 2014, and which are operational as of 2015, are not included in this analysis, yielding a conservative result. We used the Global Coal Plant Tracker[13] to confirm operational dates and the Platts World Electric Power Plants Database[14] to verify the installed capacity of each plant.[i] We are estimating the local air pollution and climate change costs of emissions for 2015.[ii]

We estimated the economic costs for local air pollution based on data from Parry, et al.[7] (IMF study), who employed the following methodological steps (See Appendix II):

1. **Determine how much pollution is inhaled by exposed populations**, both due to emissions from domestic power plants as well as emissions that may have been transported from other countries;
2. **Assess how this pollution exposure increases mortality risks**, accounting for factors, such as the age and health of the population, that affect vulnerability to pollution-related illness;
3. **Monetize the health effects**, using estimates from the OECD and corrections for national income;
4. **Express the resulting damage per unit energy of coal**.

In order to calculate the costs of local air pollution per plant, we first calculated the energy output per plant in 2015 (PJ), using average regional capacity factors from the International Energy Agency[15] and technology-specific heat rate estimates (Btu/kWh).[16] This was multiplied by the country-specific damage estimates per unit of energy to yield the total annual local air pollution costs per plant in each country. We calculated two values for local air pollution costs: a higher scenario (uncontrolled emissions) and lower scenario (average across plants within each country with some country-specific control technology), two scenarios employed by Parry, et al.,[7] from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model.[17] The GAINS model includes country-specific emission factors based on: (1) an uncontrolled emission rate; (2) an average emission rate for plants that have some control technology (e.g., SO_2 scrubber); and (3) an average emission rate across all existing plants with and without emissions control technologies. We used this approach since we do not have emission factors for the specific plants analyzed in this study. However, the country-specific emission factors give a reasonable bound for the air pollution costs within each country.

The procedure for calculating the costs of climate change impacts from coal-fired power plant emissions starts with the emission factors (kt CO_2/PJ) from Parry, et al.,[7] to obtain total annual CO_2 emissions. Using estimates of the **social cost of carbon** (\$/ t CO_2e) – the present discounted value of global damage from the future climate change associated with an additional ton of CO_2 emissions – one can then calculate the costs per year.[18] The US Government has calculated the social cost of carbon for CO_2 emitted from 2010 to 2050 for three different discount rates (2.5%, 3.0%, 5%) from 2010 to 2300.[18] We used two values for the social cost of carbon from the US Government official estimates: the average value for a metric ton of emissions in 2015 across model runs for a 3.0% discount rate and the 95th percentile value for a 3.0 % discount rate, \$36/tCO_2e and \$105/tCO_2e, respectively. The former is a central estimate, while the latter value is supposed to represent a lower probability, but higher damages estimate. These are not meant to represent upper and lower bounds for the social cost of carbon, but two reasonable values consistent with ranges used in other studies.

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[i] Only the installed capacity of units operational in 2015 is counted.

[ii] In \$2014, given that we do not have inflation rate and national income estimates yet for 2015.

RESULTS

The economic costs of emissions from the 20 OECD country ECA-financed coal plants identified in this study are estimated to be in the range of $7.7 billion to over $32.1 billion in 2015.

The costs of local air pollution from OECD country ECA-financed coal plants are estimated to be $3.6 billion under a lower scenario (assuming country-specific pollution controls) and $20.2 billion under a higher scenario (assuming no pollution controls). (See Table 1.) Likewise, the costs of climate change-causing emissions from these plants at the global level are estimated to be $4.1 billion under a lower scenario ($36/t tCO_2e) and $12.0 billion under a higher scenario ($105/ tCO_2e). These costs are only the costs of one year's worth of estimated emissions, whereas coal power plants typically have lifespans of 35 to 50 years. The high variation in costs among countries is due to both differences in ECA-financed installed capacity (11,467 MW in India vs. 206 MW in the Philippines) and hence emissions output, as well as pollution costs per GJ, which are highest in Turkey and India ($40/GJ and $12/GJ, respectively in $2010, without pollution controls).[7] Internalizing these external costs (e.g. through the use of emissions pricing) would increase the costs of power generation by an estimated $0.05/kWh - $0.27/kWh across the 8 countries.

The high end of the total economic costs in 2015 far exceeds the OECD-country ECA investment in these plants of $8.6 billion.

While one cannot directly compare the cost of externalities with investment costs, to get a sense of the magnitude of the former, on average $1 in OECD-country ECA investment generates external annual local air pollution costs of $0.40 to $2.40. However, it should be noted that we have not calculated the benefits of this investment.

While the OECD investment is a one-time investment, the external costs accumulate every year during the lifetime of the plant, until it is closed. Over 50 years of a plant's possible lifetime, $1 in OECD investment could generate more than $100 in local air pollution costs alone (no discounting), although it is unlikely that plants will not adopt some pollution control measures going forward.

Table 1. The external costs of OECD country ECA-financed coal power plant emissions per recipient country for 2015, including the costs of local air pollution and the global costs of climate change ($2015)

Country	Local Air Pollution – Higher Scenario (uncontrolled emissions) ($2015 M)	Local Air Pollution – Lower Scenario (average of plants with emission controls) ($M)	Climate Change – Higher Scenario (social cost of carbon - $105/ tCO_2e) ($M)	Climate Change – Lower Scenario (social cost of carbon - $36/ tCO_2e) ($M)	Costs per kWh - Lower Scenario (air pollution + climate change) ($)	Costs per kWh - Higher Scenario (air pollution + climate change) ($)
Chile	85	17	433	148	0.04	0.13
India	15,255	3,146	7,214	2,473	0.08	0.32
Indonesia	1,891	231	2,225	763	0.05	0.19
Mexico	96	16	361	124	0.04	0.13
Morocco	69	12	372	128	0.04	0.13
Philippines	114	9	118	40	0.05	0.22
Turkey	1,689	86	275	94	0.07	0.79
Vietnam	967	87	972	333	0.05	0.21
	20,165	3,603	11,970	4,104	0.05 (avg)	0.27 (avg)

The top-3 financiers in terms of investment and economic damages are Korea, Japan, and the United States

The majority of OECD ECA coal finance for plants operational in 2015 in the 8 countries examined ($8.6 billion) was delivered by Japan (58%), followed by Korea (23%) and the United States (11%) (See Figure 1.) However, if we look at the associated external costs of plants financed by each OECD country, Korea tops the list, followed by Japan and the United States (many of these plants have been supported simultaneously by several ECAs from different OECD countries). (See Figure 2.) This is largely due to Korean financing of the large Mundra Ultra Mega Power Project (4620 MW) in India.

Among the recipient countries, India is estimated to experience by far the greatest economic costs of local air pollution of OECD-country ECA coal finance, followed by Indonesia.

Considering only the air pollution costs, which are borne entirely by the country where the plants are located, India is estimated to experience at least 75% of the total OECD country ECA-associated local air pollution costs (Figure 3, Figure 4), principally because more than 56% of the OECD country ECA-financed installed capacity considered in this analysis is located in India.

Figure 1. The distribution of OECD country ECA coal finance by financing country for plants confirmed to be operating in 2015 Source: NRDC-OCI-WWF Coal Finance Database[12]

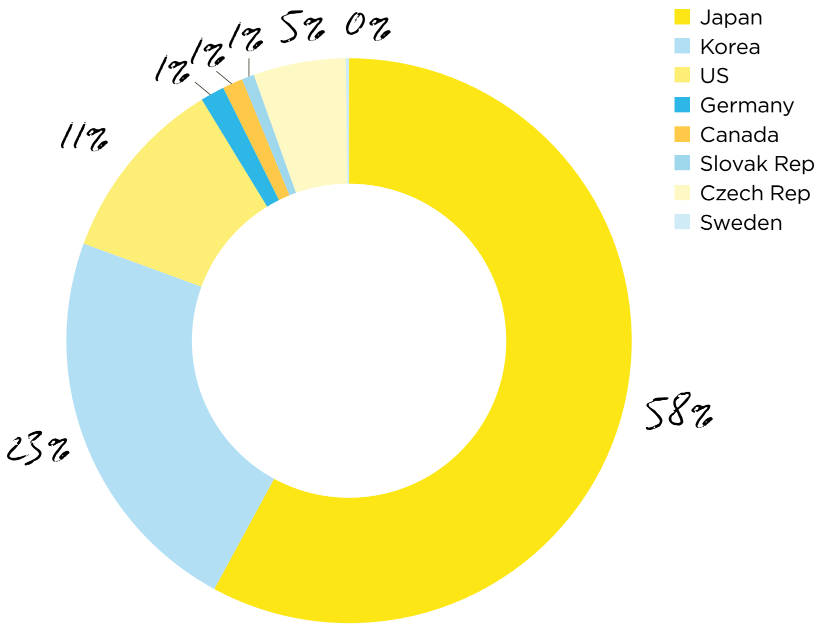


Figure 2. The distribution of the total associated local pollution costs across OECD country ECA-financed plants confirmed to be operating in 2015 per financing country (Higher Scenario) Source: Authors' calculations

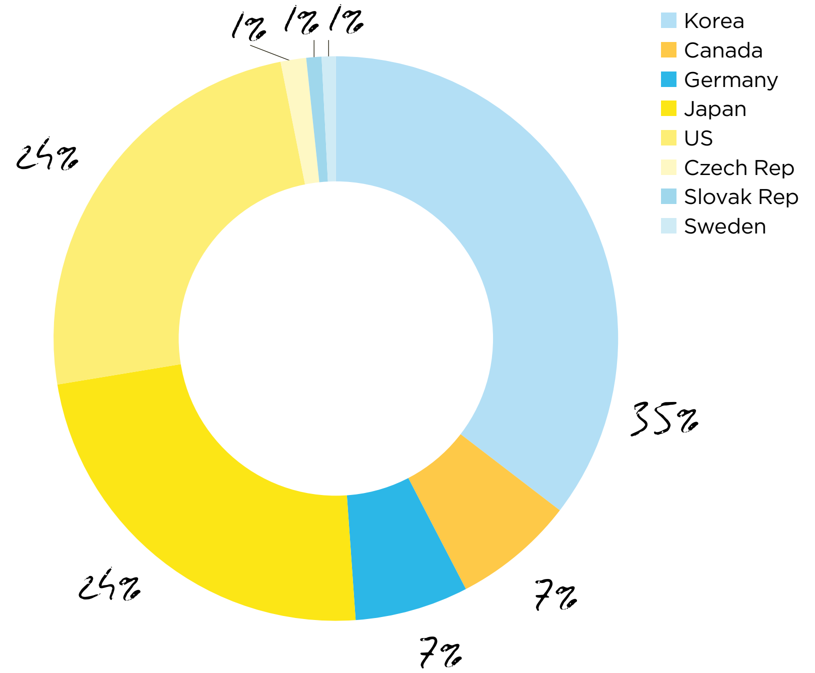


Figure 3. The recipient country breakdown of the total local air pollution costs of emissions from OECD country ECA-financed coal plants confirmed to be operating in 2015 (Higher Scenario) Source: Authors' calculations

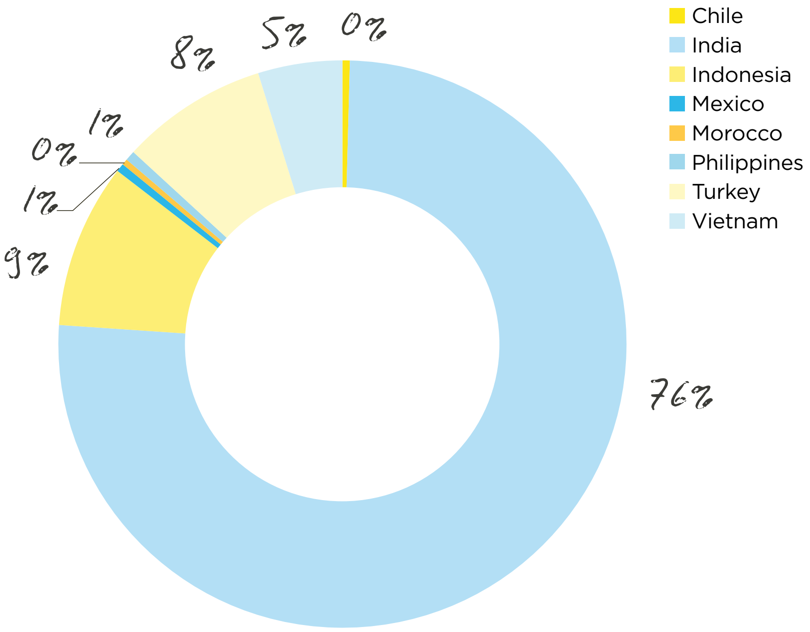
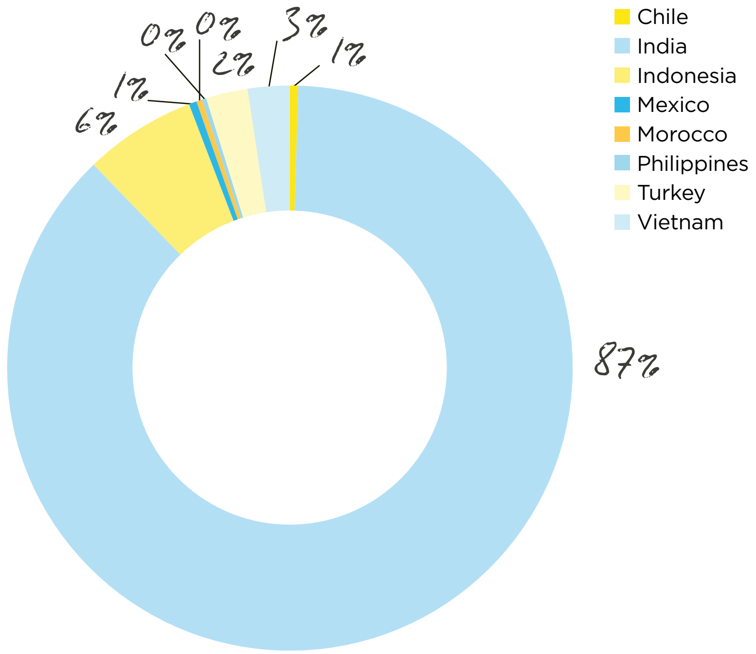


Figure 4. The recipient country breakdown of the total local air pollution costs of emissions from OECD country ECA-financed coal plants confirmed to be operating in 2015 (Lower Scenario) Source: Authors' calculations



DISCUSSION

Our analysis underestimates the costs associated with emissions from coal plants financed by OECD country ECAs

The link between air pollution and premature mortality is uncertain, so these calculations should be viewed as illustrative estimates. Nevertheless, these results should be qualitatively robust to different health damage assumptions. Furthermore, we have not explored how the specific location of a plant may mitigate some of the impacts of the air pollution. The impact of coal emissions would be more modest for plants located in sparsely populated areas or on the coast, where emissions would disperse away.

However, we have also not calculated all the economic costs of coal, either those that arise in the recipient countries examined or elsewhere. A full life cycle analysis of the costs of coal would include not only the costs of PM 2.5, SO_2, NOx, and CO_2 emissions, but also costs associated with mining (the public health burden of coal mining, methane emissions from mines, lost land value, habitat destruction, acid mine drainage), transport (death and injuries from accidents), other costs of coal combustion (environmental contamination from mercury and other metals, ecosystem damage from ozone and acid rain, climate impacts of black carbon[19] and N2O), and waste disposal (e.g. impacts of coal ash). In the US, total externalities related to coal have been estimated to be $345 billion annually ($2008), while the annual cost of emissions of air pollutants was calculated to be $187 billion.[20] Moreover, our health costs of local air pollution only factor in the costs of premature mortality, not morbidity costs (e.g. medical expenditures and lost work days associated with chronic bronchitis and acute myocardial infarction), as Parry, et al.,[7] did not model them. While mortality costs of air pollution are likely much greater than morbidity costs, morbidity costs can still be significant.[iii, 21]

There is not a complete picture of OECD-country coal finance

Moreover, there are issues of data availability and transparency that obscure a complete picture of OECD-country coal finance. The OECD Export Credit Group's secretariat does not have complete data on member's finance. The OECD is unable to report on the type of coal plant technology deployed or whether a plant uses coal for $1.2 billion and $2.5 billion in support, respectively, from 2003 to 2013. Furthermore, several countries do not report significant parts of their coal support overseas, including Japan, Korea, and Australia.[4]

[iii] Likewise the mortality benefits of PM control measures are larger than morbidity benefits. The US EPA has calculated that in 2010 the benefits of the Clean Air Act in terms of reduced PM included $1.2 trillion and $46 billion for avoided mortality and morbidity, respectively. Overall, 85% of the benefits of the Clean Air Act is attributable to reductions in premature mortality associated with reductions in PM.21. United States Environmental Protection Agency (US EPA) The Benefits and Costs of the Clean Air Act from 1990 to 2020. Report to Congress; Washington, DC, 2011.

Smoke from an underground coal fire rises from the ground near an open-cast mine in the village of Bokapahari, where a community of coal scavengers live and work in the eastern Indian state of Jharkhand.

Factoring in the negative externalities would make coal power plants far less competitive compared to renewable energy

Traditional measures of the economic assessment of electricity technologies, such as the levelized cost of electricity (LCOE - $/kWh), reflect only the discounted private costs (capital, maintenance, operations, fuel) and benefits (power generation) to companies and utilities. Such measures omit positive and negative externalities, leading to incomplete and biased results. Proper cost benefits analysis of a given project should evaluate the *full* costs of the different power generation alternatives.

It is beyond the scope of this paper to calculate the social benefits of coal power generation for the plants analyzed compared to alternative electricity sources, such as renewable energy. However, it is clear that incorporating the externalities of local air pollution and climate change would make coal power generation significantly more expensive, and thus would shift the assessment of the extent to which clean alternatives are cost-competitive.

While we did not assess specific LCOE estimates for the coal power plants listed in the study, globally, the LCOE of fossil fuel-fired power plants in 2014 was in the range of 0.045 – 0.14 $/kWh.[22] Adding costs of 0.05 $/kWh - 0.27 $/kWh associated with the externalities of coal combustion (see Table 1) would make solar PV and onshore wind much more competitive with coal in these OECD finance recipient countries given the LCOE for these renewable energy sources (see Table 2), though we acknowledge that renewables may not yet be viable in every location and that there exist additional costs associated with grid integration for renewables. Moreover, the positive externalities of electricity generation, such as poverty reduction due to energy access, would also need to be assessed for all competing electricity sources.

Table 2. The average LCOE for solar photovoltaics and wind in Africa, Asia, and South America Source: International Renewable Energy Agency[23]

Region	Solar Photovoltaics ($/kWh)	Onshore Wind ($/kWh)
Africa	0.191	0.095
Asia	0.155	0.089
South America	0.108	0.077

APPENDIX I. LIST OF COAL POWER PLANTS FINANCED BY OECD-COUNTRY ECAS BETWEEN 2007 AND 2014, AND OPERATIONAL AS OF 2015

Project	Financing ECAs	Total OECD Country ECA Investment ($)[iv]	Country	Technology	Power Plant Size (MW)[v]
Nueva Ventanas	Export-Import Bank of Korea (Kexim)	50,000,000	Chile	Subcritical	267
Angamos	Korea Export Insurance Corporation (KEIC)	675,000,000	Chile	Subcritical	540
Mahan Aluminum Smelter	Export Development Canada (EDC)	100,000,000	India	Subcritical	900
Barh Super Thermal Power Station (Stage II) (supercritical)	Euler Hermes	87,900,000	India	Supercritical	660
Jaypee Nigrie Super Thermal Power Project	Japan Bank for International Cooperation (JBIC)	110,000,000	India	Supercritical	600
Rajpura Coal-fired Power Project	JBIC, Nippon Export and Investment Insurance (NEXI)	114,363,764	India	Supercritical	1400
Mundra Ultra Mega Power Project	Kexim, KEIC	700,000,000	India	Supercritical	4620
Sasan Power Plant UMPP	Export-Import Bank - US	917,000,000	India	Supercritical	3960
Cirebon Thermal Power Plant Project	JBIC	216,000,000	Indonesia	Supercritical	700
Paiton 3 Thermal Power Plant Expansion Project	JBIC	1,458,000,000	Indonesia	Supercritical	850
Tanjung Jati B Power Plant	NEXI, JBIC	2,313,660,000	Indonesia	Subcritical	2640
Pacifico Coal Power Plant	JBIC	273,000,000	Mexico	Supercritical	700
Jorf Lasfar Energy Company 5 & 6 Coal Power Plant	JBIC, NEXI, Kexim	710,990,827	Morocco	Subcritical	700
Naga Power Plant	Kexim	170,000,000	Philippines	Subcritical	206
Yunus Emre power station	Czech Export Bank (CEB)	453,800,000	Turkey	Subcritical	290
Seydisehir Coal-Fired Station	Export-Import Bank of the Slovak Republic (Exim SR)	22,000,000	Turkey	Subcritical	13
ZETES-1 Coal-Fired Power Station	Exim SR, Exportkreditnämnden (EKN),	63,300,000	Turkey	Subcritical	160
Vung Ang 1	Euler Hermes, JBIC	79,512,684	Vietnam	Subcritical	600
Hai Phong Thermal Power Plant	JBIC	37,358,921	Vietnam	Subcritical	600
Hai Phong 2 Coal Fired Power Plant	NEXI	24,638,400	Vietnam	Subcritical	600
		8,576,524,596			

[iv] This is the total OECD country ECA investment, not the total project investment.

[v] Only includes the total installed capacity of units currently operational.

Recipient Country	OECD Country ECA financed Installed Capacity (MW)	Total OECD Country ECA Investment total ($M) (plants operational in 2015)	Total Coal Installed Capacity (MW) in Country (2015)[14]	Percent Installed Capacity
Chile	807	725.0	4,583	17.6
India	11467	2,029.3	183,004	6.3
Indonesia	4190	3,987.7	23,914	17.5
Mexico	700	273.0	5,400	13.0
Morocco	700	711.0	2,585	27.1
Philippines	206	170.0	5,769	3.6
Turkey	463	539.1	14,994	3.1
Vietnam	1800	141.5	8,704	20.7
Total	20332.8	8,576.5		

APPENDIX II. CALCULATING THE COSTS OF COAL COMBUSTION

This appendix describes the work of Parry, et al.,[7] which is the basis for the analysis in the paper. As indicated below, we made corrections to the resulting data for local air pollution to take into account inflation and changes in national per capita income from 2010 to 2015. For the costs of climate change, we used different values for the social cost of carbon.

LOCAL AIR POLLUTION

Intake fractions

The main cause of mortality risk from air pollution is particulate matter with a diameter up to 2.5 micrometers (PM 2.5), which is small enough to permeate the lungs and bloodstream. PM 2.5 is both emitted directly as a primary pollutant from fuel combustion, as well as being produced as a secondary pollutant from chemical reactions in the atmosphere involving primary pollutants, the most important of which is sulfur dioxide (SO_2), but also nitrogen oxides (NOx). The IMF methodology[7] for calculating the costs of local air pollution due to PM 2.5, SO_2, and NOx starts with the calculation of **intake fractions**, or the average pollution inhaled per unit of emissions released. Specifically the intake fractions are the grams of PM 2.5 inhaled per metric ton of primary PM 2.5, SO_2, and NOx.

The intake fractions are dependent on three main factors: (i) the height at which emissions are released; (ii) the size of the population exposed to the pollution, and (iii) meteorological and physical conditions, e.g. wind speed and direction, topography, and ambient ammonia concentrations (which catalyze atmospheric reactions of SO_2 and NOx). Population exposure is by far the most important factor and thus the only one taken into account. The approach for calculating intake fractions is based on the methodology from Zhou et al.[25] Using a model of regional air quality (CALPUFF), they estimated intake fractions for a variety of primary pollutants from 29 coal plants by simulating how emissions are transported to different regions and mapping the results on regional population density. They then used multivariate regression to estimate a set of coefficients indicating what fraction of an average plant's emissions are inhaled by an average person residing within bands of 0–100 kilometers, 100–500 kilometers, 500–1,000 kilometers, and 1,000–3,300 kilometers from the emissions source.

Parry. et al.,[7] used the Carbon Monitoring for Action (CARMA)[26] database to determine the geographical location of about 2,400 coal plants in about 110 different countries for 2009 (covering about 75%of the total electricity produced by coal power plants worldwide). LandScan data[27] are used to obtain 2010 population counts by grid cell for each of these 110 countries, as well as for countries without coal plants but where people are still vulnerable to cross-border emissions. Overlaying these data provide an estimate of the population living at each of the four distance classifications; multiplying populations in these distance categories by the corresponding coefficient from the regression equations from the work of Zhou et al[25] and then summing across the distance categories gives the intake fraction for each pollutant for each coal plant. The country average was obtained by calculating a weighted sum for individual plants, where the weights are the plant's share of total coal use.

The intake fractions were not adjusted by meteorological conditions, topography, or local ammonia concentrations, nor for the height of smokestacks. Lastly, mortality was assumed to be additive; that is, the intake fraction for one coal plant is the same, regardless of people's proximity to other coal plants.

Mortality risk

The main air pollution-related diseases are lung cancer, chronic obstructive pulmonary disease, ischemic heart disease (from reduced blood supply), and stroke. First, annual mortality rates from these four illnesses were estimated for each country, using World Health Organization Global Burden of Disease data for 2010.[28] These data include mortality rates for the 4 diseases at the regional level (with 21 regions globally) for different age classifications. Age-weighted mortality rates were then obtained using the country's population in each age class.

Relating changes in local air pollution to increased mortality is based on **concentration- response functions**, derived from US studies. Based on empirical studies, the US Environmental Protection Agency estimated that a 10 μg/m^3 increase in PM 2.5 concentrations raises all pollution-related mortality risks by 10.6%.[29] The mortality risks were extrapolated to other regions of the world with different concentrations of PM 2.5 using the above relationship for all countries.

Monetizing mortality risk

The IMF's mortality risk valuation is based on a study by the OECD, which gathered data from several hundred stated preference studies applied to environmental, health, and traffic risks in a variety of countries (mostly Canada, China, France, the United Kingdom, and the United States).[30] The OECD recommended that mortality risk should be valued at $3 million per life, ($ 2005) (i.e. the value of statistical life). (The value of statistical life varies from country to country. The value most commonly used by the US Environmental Protection Agency (EPA) in the US is $7.5 million in $2008.[20])

The value for mortality risk per life (i.e. value of the statistical life) for individual countries ($V_{country}$) was then extrapolated from the OECD (V_{OECD}) to other countries using the formula:

$$V_{country} = V_{OECD} \left(\frac{I_{country}}{I_{OECD}} \right)$$

$I_{country}$ and I_{OECD} denoted real per capita incomes in a particular country and the OECD. The ε parameter is a measure of income elasticity – how mortality value changes with income. Based on the OECD study, ε equals 0.8. The $3 million mortality value for the OECD was updated to 2010 for inflation, using the average consumer price index for the OECD and real income (using equation 1), to give V_{OECD} = $3.7 million.

The above steps allows the calculation of $ per metric ton of emissions.

Converting damage to per unit energy of coal

The damage per metric ton of emissions needs to be converted into the damage per unit energy of coal. These emission factors for each pollutant (kt/PJ) were defined relative to the energy of coal, not metric tons, because of the significant variation of heat content across coal types. The estimates are derived from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model.[17] The GAINS model estimates historic emissions of 10 air pollutants and 6 GHGs for each country based emissions inventories and other datasets, projects emissions based on future economic activities, and then estimates for each country/region the potential emission reductions and costs for about 2000 specific emission control measures.

The GAINs model calculates an uncontrolled region-specific emission factor, based on properties of the coal used in each country. For calculating SO_2 emissions, for example, the uncontrolled emission factor (EF_U) is a function of heat value per unit weight (e.g. GJ/ton of coal) (*hv*), the sulfur content per unit weight of coal (*sc*) combusted in that region, and the fraction that is retained in ash rather than being emitted into atmosphere (*sr*):

$$EF_U = \left(\frac{sc}{hv} \right) (1 - sr)$$

The controlled emission factor (EF_C) for control technology *t* is:

$$EF_C = EF_U(1 - re_t)$$

Where re_t is the fraction of emissions that are abated. For control of sulfur emissions, the control measures include: the use of low-sulfur fuels, including fuel desulfurization; in-furnace control of SO_2 emissions (e.g., through limestone injection or with several types of fluidized bed combustion); and flue gas desulfurization processes, etc. The GAINS model has a database of the control technologies used per region, the fraction of emissions abated for each technology, and the share of that technology in each region.[31] The model also calculates an emissions factor for a representative plant that has some control technology and an average emission factor across all existing plants with and without emissions control technologies (weighted by the share of fuel input for the plants). The emission factors allow the conversion to costs per unit energy ($/GJ) of coal combustion for each pollutant. We calculated two values for local air pollution costs: a higher scenario (uncontrolled emissions) and lower scenario (average across plants within each country with some country-specific control technology). Since we do not have emission factors for the specific plants analyzed in this study, the country-specific emission factors give a reasonable bound for the air pollution costs.

CLIMATE CHANGE IMPACTS

The cost of climate change impacts from coal-fired power plant emissions is based on estimates of the **social cost of carbon** (\$/t CO_2e), i.e. the present discounted value of global damage from the future climate change associated with an additional ton of CO_2 emissions. Using 3 global integrated assessment models (IAMs), the US Government has calculated the social cost of carbon for CO_2 emitted from 2010 to 2050 for 3 different discount rates (2.5%, 3.0%, 5%) from 2010 to 2300.[18] We used two values for the social cost of carbon from these official US Government estimates: the average value for a metric ton of emissions in 2015 across model runs for a 3.0% discount rate and the 95th percentile value for a 3.0% discount rate, \$36/tCO_2e and \$105 tCO_2e, respectively. The former is a central estimate, while the latter value is supposed to represent a lower probability, but higher damages estimate. In comparison, Parry, et al.,[7] used only one value for social cost of carbon - \$35/tCO_2e. Epstein et al.[20] used values of \$10/tCO_2e and \$100/tCO_2e, in line with a National Research Council study.[32]

The appropriate discount rate to use in climate change economic analyses is contentious. Some would argue that due to concerns about inter-generational equity, we should not discount future welfare. A high discount rate would make the costs of climate impacts that future generations experience very small compared to the costs of action now. The Stern Review[6] used an overall discount rate of 1.4, in part reflecting this argument. Others argue that the discount rate should reflect the opportunity cost of capital (e.g. rate of return for an investment in the private sector or the borrowing rate for a country). Nordhaus[33] uses a default discount rate of 4% in his Dynamic Integrated Climate-Economy (DICE) model, one of the models which the US Government used to estimate the social cost of carbon. Wagner and Weitzman[34] argue that because of uncertainty around what the discount rate should be far into the future, a low discount rate is justified.

It should also be noted that the 3 IAMs used to calculate the social cost of carbon also rely on estimates of the value of a statistical life (VSL) or similar metrics. The FUND (the Climate Framework for Uncertainty Negotiation, and Distribution) model applies 200 times per capita income as the value of an avoided mortality[35], while the DICE model assumes a year of life lost to be two years of per capita income.[36] The PAGE model lacks a simple VSL measure.[37]

We have not included the climate change impacts of other products of coal combustion, such as short-lived greenhouse pollutants, in particular, black carbon.[19]

CALCULATING THE COSTS PER COAL PLANT

To calculate the total economic costs per coal-fired power plant per year, first the installed capacity of each plant (MW) from the database on international coal finance[12] is converted to power (MWh), using country/region-specific capacity factors for coal in 2012 (OECD Americas for Chile and Mexico; India; non-OECD Asia for Indonesia, Philippines, and Vietnam; non-OECD for Morocco, OECD for Turkey), based on International Energy Agency figures for generation and installed capacity.[15] This figure is then converted to total energy (PJ), using the heat rates (Btu/kWh) from a US Environmental Protection Agency (EPA) study.[16] The study includes heat rates for specific coal technologies (subcritical or supercritical), installed capacity (400 MW, 600 MW, 900 MW), and coal type. The heat rate is based on the unit size, not the overall installed capacity of the plant, assuming bituminous coal.

For local air pollution, we used the above country-specific costs per unit energy (\$/PJ) to calculate total air pollution costs per plant. The original costs per unit energy were calculated for 2010; these figures are updated to 2015, using equation 1, to account for changes in per capital national income (GDP, Purchasing Power Parity) and country-specific inflation (based on the average consumer price index), using the IMF's World Economic Outlook estimates.[38]

For the costs of climate change, we used the above emissions factor for CO_2 (kt/PJ) to calculate total CO_2 emissions per year for each plant; multiplying by the social cost of carbon value then gives the climate change cost for that plant in the given year. The original social cost of carbon values are in 2007 US dollars; the figures are updated for 2015 to account for inflation, using the most recent average value for inflation (August 2015) in the OECD countries (consumer price index).[39]

Table 3. Heat rates (Btu/kWh) used in the analysis. Source: US EPA[16]

Plant type	400 MW	600 MW	900 MW
Subcritical	9349	9302	9291
Supercritical	9058	9017	8990
UCS	8924	8874	8855

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