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Projecting the external health costs of a coal-fired power plant: The case of Kusile

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Abstract
We examine an important subset of the expected health costs associated with the commissioning of Kusile, a new coal-fired electricity generation plant in South Africa. The subset of health impacts focuses on sulphur dioxides, nitrous oxides and large particulate matter (greater than 10 mm). The analysis makes use of the Impact Pathway Approach combined with the data transfer methodology. The plant, which is expected to contribute 4 800 MW of additional electricity to the South African grid is found to have modest health impacts, partly due to the limited additional pollutant emissions expected at the plant. Specifically, additional localised external health costs are found to be in the region of 0.09c/kWh to 6.08c/kWh. Limitations of the analysis are also examined.

Keywords: Impact Pathway Approach; health cost externalities; Kusile

1. Introduction

The potent mixture of economic development and a lack of investment in its power generation infrastructure and capacity has resulted in South Africa reaching its maximum electricity production capacity. Faced with this challenge, the national power utility, Eskom, has commissioned a number of new power plants to be constructed over the next five years (Department of Energy, 2009). The construction of two new coal-fired power plants – Kusile in eMalahleni, Mpumalanga and Medupi in Lephalale, Limpopo – is underway. South African reliance on coal for electricity generation will therefore increase substantially.1

The combustion process produces large quantities of gaseous and solid waste that are mainly released into the air, or disposed of in large ash dumps or sludge and slurry ponds. The gaseous emissions contain a potent mixture of pollutants. Various studies have shown these pollutants to have adverse effects through air pollution (Pope, III *et al.*, 2009; Dominici *et al.*, 2006; Van Horen, 1996) and water pollution (Van Horen, 1996), adverse effects on biodiversity (Zvereva *et al.*, 2008; Turpie *et al.*, 2004), adverse effects on buildings (Charola *et al.*, 2007; Van Horen, 1996; Schreurs, 2011), and to contribute towards global climate change (Turpie *et al.*, 2004). To add fuel to the fire, so to speak, burning coal produces one and a half times the CO_2 emissions of oil combustion and twice the amount of CO_2 emissions from natural gas combustion, while producing the same amount of energy (Epstein *et al.*, 2011). This difference holds true for many other pollutants produced during the electricity generation process.

With regards to solid waste, ash dumps have been found to contribute to air pollution, particularly in the form a particulate matter (PM) when fly ash from ash dumps is carried into the atmosphere by the wind. Sludge and slurry pools have also been linked to ground water contamination, which has a variety of health and environmental consequences (Epstein *et al.*, 2011). With this in mind, coal-fired power plants are a major contributor to atmospheric pollution levels. Multiple local and international studies have sought to quantify the socio-economic and environmental damages associated with pollutants from coal-fired electricity generation. We add to this literature, through the examination of the potential health effects that could arise from one new coal-fired power generation plant – Kusile, specifically, the localised health impacts and costs associated with these impacts. The analysis is based upon the Impact Pathway Approach (IPA).

In order to assess the full cost related to Kusile all of the above-mentioned externalities would have to be considered. This paper therefore forms part of a set of papers which aim to provide a comprehensive overview of the external cost associated with Kusile (Blignaut, 2012; Inglesi-Lotz & Blignaut, 2012; Nkambule & Blignaut, 2012).

The remainder of this study continues with an examination of previous literature, in Section 2. Section 3 describes the Impact Pathway Approach and the underlying assumptions of the analysis. Section 4 presents the results of the analysis and a brief discussion of the results and a conclusion are presented in Section 5.

2. Literature review

Growth and development necessitates the production of electricity. As the need for electricity rises with development, questions regarding potential side effects have also begun to surface. Consequently, over the past three decades, identifying and quantifying the externalities associated with electricity generation and the impact of a growing electricity sector have come to the fore. Externalities arise when the social and marginal costs of electricity generation differ, which means that the market price does not fully reflect the resource value. Therefore, individual welfare does not reflect the entire cost of the good or service (Baumol and Oats, 1988; Pearce and Turner, 1990). The focus of this study is on health externalities, specifically the cost of health externalities.

2.1 Health consequences of pollution

The combustion of coal during the electricity generation process produces carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), particulate matter (PM), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), mercury (Hg), and a wide range of carcinogenic chemicals and heavy metals (Levy *et al.,* 2009). While the chemical nature of PM is important, it varies significantly, prompting researchers to use the diameter of the particulates, as this affects lung penetration (Norman *et al.,* 2007).[2] In epidemiological studies, $PM_{2.5}$ and PM_{10} are most often selected as relevant exposure metrics (Norman *et al.*, 2007).

Significant associations have been found between outdoor air pollution levels and morbidity and mortality outcomes. Various epidemiological studies find these pollutants to contribute to bronchitis, asthma and lung cancer, and also hospital admissions or emergency room visits related to respiratory ailments, cardiac conditions, asthma, coronary obstructive pulmonary disease (Norman *et al.,* 2007; Levy *et al.,* 2009; Epstein *et al.,* 2011). While there is a link between pollutant exposure and deteriorating health, attributing the incidence of epidemiological outcomes to specific pollutants is complex, mainly due to strong correlations found between the various pollutants in high concentrations (Sarnat *et al.,* 2001). Therefore, a pollutant-by-pollutant incidence analysis could greatly overestimate the health impacts of air pollution (Künzli *et al.,* 2000).[3]

2.2 Costing methodologies

There are two fundamental approaches to evaluating externalities, namely, the abatement cost approach and the damage cost approach. The abatement cost approach considers the cost of controlling damage, as a proxy for the actual damages. Although limited data is needed, low levels of accuracy also arise (Owen, 2004). The top-down and the bottom-up damage cost approaches, which use actual costs and benefits that can be tied to the externality rather than the cost of avoiding that damage, are more common. Top-down estimates use aggregate data, and are, therefore, not relevant for site-specific evaluations. A bottom-up approach, also referred to as the Impact Pathway Approach (IPA), track pollutants from their initial source and monetise their effects (Thopil & Pouris, 2010). As this approach allows for site-specific evaluation, it is the method used in this study; further discussion of the method and requirements are presented in Section 3.

2.3 International studies

The bulk of electricity sector externality studies focus on the United States (Oak Ridge National Laboratory and Resources for the Future [ORNL/RfR], 1995; Rowe *et al.,* 1994) and various countries in Europe (ETSU, 1995; Friedrich and Voss, 1993; Hohmeyer, 1988; Ottinger *et al.*, 1991; Pearce *et al.,* 1992). Table 1 provides a price-adjusted summary, in ranges, from a number of international externality studies and indicates the study method of each. Included within each range is a value for the health cost externalities. Our comments, however, focus on the method applied in this research, the bottom-up approach.[4]

ORNL/RfF (1995) is representative of early attempts at the bottom-up approach, and focused on the impacts of air pollution on human health and other non-environmental damages. Owing to their inability to control for a number of environmental impacts, the damage cost estimates are low, which highlights the need for further evaluation efforts. The RCG/Tellus initiative (Rowe *et al.,* 1995) applies a similar method for New York. Although not necessarily improving on ORNL/RfF, RCG/Tellus developed EXMOD which is a useful computerised model. The modelling was further developed, when the European commission and the US Department of Energy launched the EC/US Fuel Cycles Study in 1991 (Thopil & Pouris, 2010), referred to as the ExternE program. Earlier ExternE

Table 1: Selected external studies of coal-fired electricity using different approaches
Source: Thopil and Pouris (2010:2)

Study	*Method*	*Region*	*External cost USc/kWh*
Schuman & Cavanagh (1982)	Abatement cost	United States	0.07 – 54.64
Hohmeyer (1988)	Top-down damage cost	Germany	12.42 – 28.33
Ottinger et al. (1991)	Top-down damage cost	United States	4.04 – 10.99
Pearce et al. (1992)	Top-down damage cost	UK	3.31 – 17.89
Faaij et al. (1998)	Top-down damage cost	The Netherlands	4.93
ORNL/RfF (1995)	Bottom-up damage cost	United States	0.14 – 0.60
European Commission (1995)	Bottom-up damage cost	UK/Germany	1.21 – 2.96
Rowe et al. (1994)	Bottom-up damage cost	United States	0.38
Bhattacharyya (1997)	Bottom-up damage cost	India	1.68
European Commission (1999)	Bottom-up damage cost	European Union	1.04 – 89.80
Maddison (1999)	Bottom-up damage cost	UK/Germany	0.38 – 0.88
Rafaj & Kypreos (2007)	Bottom-up damage cost	Global average	9.08
Klaassen & Riahi (2007)	Bottom-up and top-down	Global average	4.84
Dutkiewicz & De Villiers (1993)	Top-down damage cost	South Africa	0.48 1
Van Horen (1996)	Bottom-up damage cost	South Africa	1.03 - 5.77[1]
Spalding-Fecher & Matibe (2003)	Bottom-up damage cost	South Africa	0.40 - 2.68[1]

Note: 1) Values are given in terms of 2006 US cents, as based on the 2006 Rand/US$ middle rate.

studies (European Commission, 1995; European Commission, 1999) made substantial advances in the methodologies associated with valuation and provide deeper insight into the data and pathway requirements for environmental externality valuation.

2.4 South African studies

Thopil and Pouris (2010) provide a useful summary of electricity externality analysis in South Africa. Electricity externalities were first addressed and quantified by Dutkiewicz and De Villiers (1993) in a Department of Minerals and Energy Affairs study. Their top-down approach finds costs that could be placed in the lower range of international studies, although they suggest that the inclusion of aesthetic effects (e.g. noise pollution) could improve the analysis. Van Horen (1996) is the most extensive electricity externality study to date; with an emphasis on coal and nuclear power, using the bottom-up approach to compare the external costs across these different forms of electricity generation. The study found that the release of greenhouse gasses (GHG) contributes the most to the external costs, while the health impact of air emissions contribute to a lesser extent. However, Van Horen argues for the use of more relevant dose-response functions and the inclusion of the cost of air pollution stemming from ash dumps.

Spalding-Fecher and Matibe (2003) and Spalding-Fecher (2005) expanded Van Horen's analysis, including the incorporation of updated power generation infrastructure data and the external benefits associated with household electrification through, for example, the decreased inhalation of smoke from indoor fires. Despite these improvements, Spalding-Fecher and Matibe (2003) suggest further refinements, such as the use of impact pathways more suited to the South African context, as well as local dose-response functions. The estimates from these three studies are presented at the end of Table 1, based on inflation-adjusted values presented in Thopil and Pouris (2010). As with the previous studies, health externalities are included within these costs.

3. Data and methodology

As noted earlier, this analysis is based on the IPA (Rowe *et al.,* 1994; European Commission, 1999; Rafaj and Kypreos, 2007; Klaassen and Riahi, 2007), which follows pollutants from their initial source, estimates their impacts and calculates monetary values related to these impacts. Given that the IPA corresponds with the real-world sequence of events and consequences associated with electricity generation, it is intuitively appealing and is generally regarded as the benchmark model (Rowe *et al.,* 1995), although there are limitations. The approach is data-intensive, requiring professional judgements regarding the data; and as such, the results can be sensitive to these judgements. Relatedly, studies of this nature are best conducted when data is readily available and impact pathways are easily established. Although Van Horen (1996), as well as Spalding-Fecher and Matibe (2003), suggest revision to the impact pathways and dose-response functions in South Africa, Van Horen (1996) further notes that there is a large body of relevant information available in South Africa making an IPA evaluation possible.

In order to quantify the health impacts caused by the pollutants released by a coal-fired power plant, information for the four major steps in the IPA is required. These steps, as summarised by Van Horen (1996), are: (i) determine power station pollution emissions; (ii) track pollutant dispersion and deposition; (iii) evaluate dose responses to pollution exposure; and (iv) value the increased morbidity and mortality associated with those dose responses. Once monetary values have been linked to morbidity and mortality, the bridge between market cost and social cost can be, at least partially, addressed.

3.1 Emissions

In South Africa, low quality coal, which would otherwise have little other economic use (Van Horen, 1996), is the energy source for electricity generation.[5] The coal is laid down in thick level seams at shallow depths, such that extraction is relatively cheap and easy; however, in addition to its low quality the coal also has a high ash content (Department of Energy, 2010).[6] The exact content of ash and sulphur is not available at the power plant level. Since the exact composition of the emissions cannot be precisely determined, $PM_{2.5}$ and PM_{10} are most often used to represent human exposure to air pollution (Norman *et al.,* 2007). Owing to data limitations, only PM_{10} will be used to represent PM, while SO_2 and NO_2 will also be considered in this analysis.[7]

Since the Kusile plant is yet to be completed, emissions data is based on experiences from the Kendal coal-fired power station, located in close proximity to Kusile. Comparing Kendal and Kusile, based on their technical and operational specifications it is clear that the two plants are rather similar (see Tables 2 and 3). In Tables 2 and 3, two different capacity values are used for Kusile, reflecting the difference between the actual capacity (4 800 MW) and the environmental impact assessment (EIA) calculation capacity (5 400 MW). Since the volume of emissions is linearly related to the capacity of the plant, multiplying the emission data with the ratio of the two capacities (4 800/5 400 = 0.8889) yields projected emissions for Kusile. These emissions contribute to the overall ambient pollution levels in the area and, therefore, are used in the dispersion model (see Table 4).

3.2 Dispersion

The dispersion of pollutants is determined by the physical characteristics of the plant (i.e. chimney stack height; the speed, volume and temperature of gas emissions; and ash dump characteristics) and atmospheric conditions (i.e. wind patterns, mixing heights and atmospheric stability) (Van Horen, 1996). Dispersion models indicate ambient concentrations of various pollutants across time and space, following the exit of emissions from the chimney stack. These models are typically local, focussing on a 50 km radius from the plant. Beyond this distance, the pollutants are depleted through chemical transformation, dry deposition and precipitation. While the Gaussian plume model is often used to

Table 2: Technical specifications for Kendal and Kusile power plants

Source: Wassung (2010: 10–13)

Power plant	*Province*	*Capacity*	*Cooling system*	*Pollution control technology*	*Year*
Kendal	Mpumalanga	4 116 MW	Indirect dry	ESP [2]	1993
Kusile	Mpumalanga	4 800 MW [1]	Direct dry	ESP [2], FGD [3]	2014–18

Notes:

1. Actual capacity of Kusile.
2. Electrostatic precipitator for controlling dust.
3. Flue gas desulphurisation for controlling SO_2.

Table 3: Stack parameters for Kendal and Kusile plants

Source: Thomas and Scorgie (2006: 4.7, 5.3)

Power station	*Capacity*	*Number of stacks*	*Stack height (m)*	*Diameter (m)*	*Exit velocity (m/s)*	*Temperature (°K)*
Kendal	4 116 MW	2	275	13.51	24.08	399
Kusile	5 400 MW [1]	2	150 – 300 [2]	12.82	26	403

Notes:

1. Proposed capacity used in EIA calculations.
2. Three stack height scenarios were considered in EIA calculations.

Table 4: Total emissions for current operating conditions for 2003
Source: Thomas and Scorgie (2006: 4.13, 5.3, 5.7)

Power station	*Capacity*	*Tonnes per annum*				
		SO_2	*NO_X*	*NO*	*NO_2*	*PM*
Kendal (2003)	4 116 MW	321 441	NQ [5]	73 282	2 293	3 495
Kendal (proposed 2009)	4 116 MW	336 084	NQ [5]	76 620	2 398	3 654
Kusile (proposed: EIA) [1]	5 400 MW [3]	364 082	87,361	55 835	1 747	7 947
Kusile (proposed: actual) [2]	4 800 MW [4]	323 628	77,654	49 631	1 553	7 064

Notes:

1. Assuming 0% control efficiency for SO_2.
2. Figures determined through calculation: [Kusile (proposed: EIA) values]*(4800/5400).
3. Proposed capacity used in EIA calculations.
4. Actual capacity of Kusile.
5. Not quantified.

estimate local dispersion, it will not be used here. Spalding-Fecher and Matibe (2003) do not believe the model matches the conditions of the Highveld.

Owing to the detailed scientific knowledge required to construct and estimate pollution dispersion models, the dispersion calculations published in Kusile's EIA are used, while existing exposure response functions (ERFs) have been sourced from the literature. The data transfer method is applied, which first requires the identification of existing values that can be transferred into the current study. Second, the appropriateness of the existing values must be evaluated to ensure that the values are suitable. Third, the quality of the studies to be transferred must be assessed, since this will affect the quality of the current study. Lastly, the values may be adjusted to better suit the context of the current study, possibly requiring additional information (Boyle and Bergstrom, 1992). There are, however, some drawbacks to this approach. King and Mazzotta (2000) caution against extrapolating results beyond the scope of the transfer studies. Use of the data transfer method is, however, common when data limitations would make analysis impossible (Sakulniyomporn *et al.,* 2011).

Modelling dispersion patterns require sophisticated software, such as the CALMET/CALLPUFF system. Although not used in this analysis, CALMET/CALLPUFF was used in the air quality impact assessment (AQIA) report (Thomas and Scorgie, 2006) and the EIA (Ninham Shand, 2007). The software consists of three components (Scire *et al*., 2000): CALMET, CALPUFF and CALPOST. CALMET is a diagnostic meteorological model that generates hourly wind and temperature data. CALPUFF, a multi-layer, multi-species, non-steady-state, Lagrangian Gaussian puff model, uses this data to model movement and variation in pollutant levels. The Lagrangian Gaussian puff model addresses the suitability concerns raised by Spalding-Fecher and Matibe (2003). Lastly, CALPOST summarises the simulation results (Sakulniyomporn *et al.,* 2011). The dispersion results from the AQIA report are used to identify the at-risk communities surrounding the site of Kusile.

From the AQIA, a number of residential areas have been identified in close proximity to Kusile. The towns of Phola and Ogies are located 10–18 km east of the site, while numerous smaller areas (including, but not limited to, Voltargo, Cologne, Klippoortjie, Madressa, Witcons, Saaiwater, Tweefontein and Klipplaat) are also nearby (Figure 1). The largest residential area within 30 km of Kusile is eMalahleni (Ninham Shand, 2007).[8] Two ambient air quality monitoring stations are operated by Eskom in the region; Kendal 2 and Kendal B are situated within the zone of maximum ground level concentration (GLC), defined as a 25 km radius around the plant (Ninham Shand, 2007).

For the purpose of this study, the costs associated with SO_2, NO_2, PM_{10} and a selection of other trace compounds – arsenic (As), chromium VI (Cr VI), lead (Pb) and nickel (Ni) – are considered, since these pollutants are the major contributors to pollution-related health issues.[9] In order to assess whether pollutant concentrations exceed health thresholds, pollution limits must be defined. Table 5 provides a summary of some maximum and minimum air quality standards in South Africa, as well as the guideline used in the EIA calculations. Since there are numerous local and international air quality standards, only the most and least strict standards, in addition to the standard decided upon in the EIA are given in Table 5.

Although hourly, daily and annual average health standard exceedence data is available, only annual average concentration findings are used, since the cumulative annual health effect and cost of the air pollution are to be considered (see Tables 6, 7 and 8). The base case – that is, this situation without Kusile – as well as three unique scenarios with different stack heights are considered for the pollutants. The scenarios are evaluated in the context of zero SO_2 control efficiency and 90% control

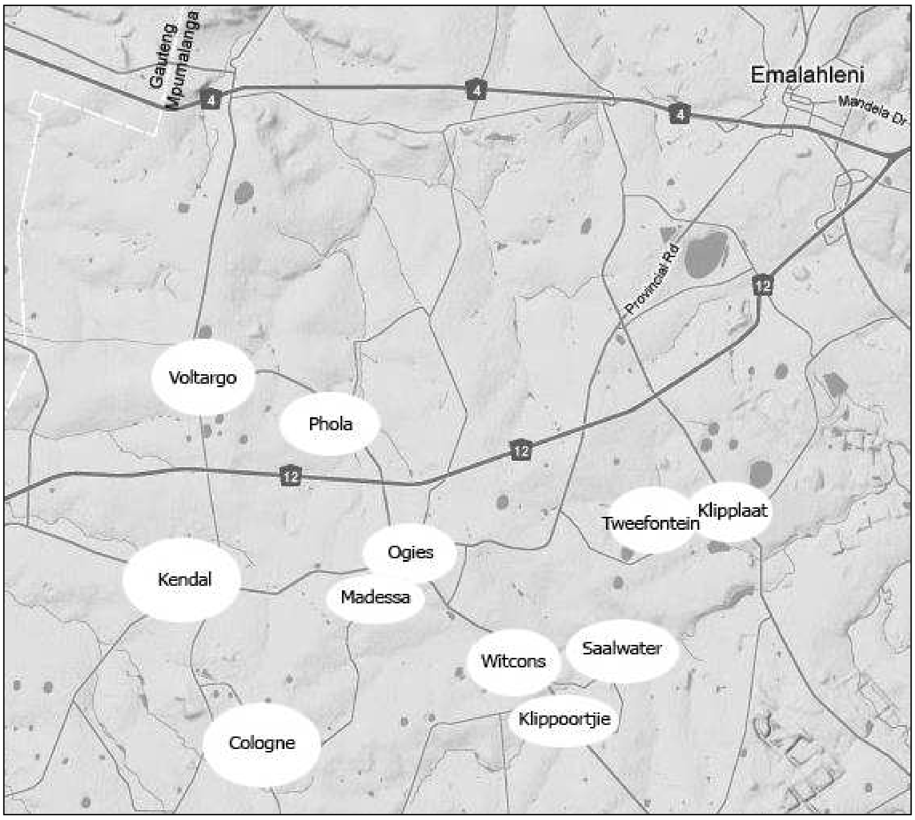

Figure 1: Communities within close proximity of the Kusile power plant and their respective population densities
Source: Thomas and Scorgie (2006:1–6)

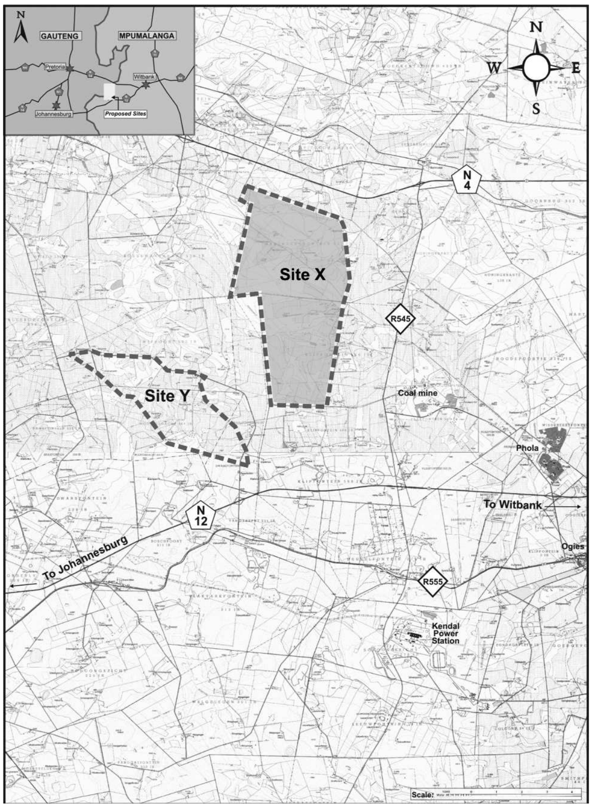

Figure 2: Location of the Kusile power plant (site X)
Source: Ninham Shand (2007: 2)

Table 5: Selected air quality standards (human health only)
Source: Thomas and Scorgie (2006: 2.3, 2.5, 2.7)

	Annual average concentrations (μgm^{-3})		
	Minimum	*Maximum*	*EIA*
SO_2	20	80	50
NO_2	40	100	40
PM_{10}	20	60	40
		Description	
SO_2	US EPA; WB: TPG	UK; EC	*SA*
NO_2	US EPA	UK	*SA, WHO, EC and UK*
PM_{10}	SA standards	EC	*SANS, EC and UK*

efficiency. A positive value means that the annual concentration exceeds the proposed air quality limits. Given the strictest air quality standards, the baseline SO_2 concentration exceeds air quality limits. Therefore, even without Kusile's presence, SO_2 levels in the area are deemed too high (Ninham Shand, 2007). Exceedence also occurs in the zone of maximum GLC, when considering the EIA air quality standards, although flue gas desulphurisation (FGD) does reduce its magnitude.

Table 6: Calculated pollutant concentrations for Kusile (4 800 MW)

	Annual average concentrations (μgm^{-3})						
	Scenario	*0% Efficiency*			*90% Efficiency*		
	Stack height	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*
GLC	SO_2	69.8	63.6	59.1	50.2	50.2	49.3
	NO_2	9.8	9.8	9.8	9.8	9.8	9.8
	PM_{10}	84.8	84.8	84.8	83.9	83.9	83.9
Phola	SO_2	53.9	48.6	45.0	35.2	35.2	34.3
	NO_2	9.5	9.0	8.7	9.5	9.0	8.7
	PM_{10}	25.5	25.5	25.5	25.5	27.3	25.5

Table 7: Additional pollutant added by Kusile to the baseline conditions

	Annual average concentrations (μgm^{-3})						
	Scenario	*0% Efficiency*			*90% Efficiency*		
	Stack height	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*
GLC	SO_2	25.8	19.6	15.1	6.2	6.2	5.3
	NO_2	1.8	1.8	1.8	1.8	1.8	1.8
	PM_{10}	1.8	1.8	1.8	0.9	0.9	0.9
Phola	SO_2	24.9	19.6	16.0	6.2	6.2	5.3
	NO_2	3.6	3.1	2.8	3.6	3.1	2.8
	PM_{10}	19.7	19.7	19.7	19.7	21.5	19.7

Predicted levels of NO_2 do no not exceed even the strictest of air quality standards. The NO_2 values for the three scenarios compare very closely to those of the baseline values, suggesting that existing sources of NO_2 are the main contributors to ambient levels of the gas.

Particulate matter has a more prominent effect, however. Air quality limits in the GLC zone are always exceeded; all Kusile scenarios exceed the most stringent air quality limit at Phola, as well. Therefore, PM_{10} could contribute significantly to the incidence of disease related to this pollutant. Table 7 shows the additional pollutants contributed by Kusile above baseline. Only the actual capacity (4 800 MW) emissions are considered, and these values are used to determine the number of people affected by various pollution-related illnesses, based on incident rates sourced from the literature (Sakulniyomporn *et al.,* 2011).

Table 8: Aerial concentrations of selected metal compounds

Compound	*Annual average concentrations (μgm^{-3})* *Baseline*	*Exceedence*
As	3.14E-05	1.68E-05
Cr VI	6.20E-04	3.30E-04
Pb	1.29E-04	6.44E-05
Ni	1.86E-04	9.56E-05

Finally, Ninham Shand (2007) notes that elevated SO_2 concentrations identified in the study have significant potential health risk, particularly when coupled with elevated levels of particulate matter. Although there is a potentially high risk in the Phola residential area, exceedence was infrequent at the reference level, hence, the health effects depend on whether individuals exposed to the pollution are sensitive to the impacts of SO_2 at the time of exceedance. Nonetheless, the SO_2 levels are cause for concern.[10]

The largest residential populations within the dispersion area are found at Phola and Ogies, although only Phola will be considered on an individual level, since it represents the most significant (in terms of size) residential area within the impact area. Detailed population data on the impact area could not be found and, hence, calculations are based on aggregate data for the eMalahleni Local Municipality, where Kusile is situated. According to MPG (2011), the eMalahleni Local Municipality covers approximately 2 677.67 km^2 with an estimated 425 925 people living in the municipality. The study relies on the population density reported by the EIA, given as a range of between 1 000 and 5 000 people per km^2, which are used for low and high value calculations, respectively.

The zone of maximum GLC covers a 25 km radius emanating from the plant. Both Phola and Ogies fall within this area. Therefore, any cost estimation in the zone will represent the total cost of the impact area. In order to calculate the population within this area, the average population density of the eMalahleni Local Municipality was calculated

(159 persons per km^2), which compares well with the value of 100 persons per km^2 given in the AQIA for the majority of the maximum GLC zone (Thomas and Scorgie, 2006). Multiplying the average population density with the total area covered in the zone gives the total affected population of 312 450.

3.3 Pollution impacts

To link the incidence of health damages to pollutant concentrations, ERFs are needed. ERFs relate the quantity of pollutant that affects a receptor to the physical impact on that receptor (Rabl, 2011). In general, epidemiological studies report the incidence of illness in terms of relative risk, requiring calculations to assess the ERFs in terms of relative risk values. The expected outcomes are given by Sakulniyomporn *et al.* (2011:3467) and Thomas and Scorgie (2006:2.16), based on the assumption of zero-threshold linear ERFs.

$$ERF(r,C(r,Q)) = SERF(r) \times C(r,Q) \qquad (1)$$

$$SERF = IRR \times Baseline \times F_{PQP} \qquad (2)$$

$C(r,Q)$ represents the average incremental change in ground-level concentration (μgm^{-3}) at position vector r and emission rate Q. The slope, $SERF$, is calculated from equation (2). IRR refers to the increment of relative risk (percent/μgm^{-3}), which represents the marginal health risk of pollutant concentrations. The baseline rate is the nominal rate of occurrence of the considered disease, and F_{POP} denotes the fraction of the population at risk of said disease, typically based on age-specific groups.

When estimating the health cost associated with air pollution, the problem that arises is that relatively high doses are needed in order to obtain observable non-zero epidemiological responses – unless the sample is very large. The required doses are usually far in excess of typical ambient concentrations (Rabl, 2011). Therefore, by definition, lower doses are without effect. Furthermore, the susceptibility of individuals to harmful chemicals can vary widely. This variation comes about as a result of different lifestyles, varying diets, or other exposures and pre-existing health outcomes that may contribute to the effect. These differences make establishing thresholds for a large diverse population difficult (Bull, 2001: 2–3). Consequently, studies which aim to monetise the externalities related to air pollution will often include the zero-threshold assumption (Hainoun *et al.,* 2009; Sakulniyomporn *et al.,* 2011). Typically these studies would also be conducted on a national level to ensure a large population size. In cases where the costs are localised, the population in that area would be more homogenous than a national population, resulting in the inability to use the zero-threshold assumption.

Kusile is situated in the eMalahleni municipality where mining activity is prominent. Mining relies greatly on a migrant workforce for its labour supply with migrant workers originating from all over South Africa. These migrant workers would have been exposed to a variety of different environmental and social factors and it is this variable characteristic which would bring needed heterogeneity to the local population. Therefore, the zero-threshold is deemed appropriate for this analysis.

The scope of health issues related to air pollution is broad, yielding a large number of health concerns linked to air pollution. Since it is not feasible to include every single ailment, only the following health issues are considered (Sakulniyomporn *et al.,* 2011): chronic bronchitis (CB) in adults; respiratory hospital admission (RHA); cardiovascular hospital admissions (CHA); emergency room visits (ERV); acute bronchitis (AB) in children; asthma attacks (ASA) in children; asthma attacks (ASA) in adults; restricted activity days (RAD) in adults; and days with acute respiratory symptoms (ARS). Lung cancer is also considered.

The response of populations to various pollutants is well documented for the developed world; however, fewer studies have attempted to quantify these responses in developing countries. Table 9 provides a summary of the incident rates used in this study. Note that for all outcomes other than cancer, central, low and high values are reported, based on Sakulniyomporn *et al.* (2011). For lung cancer, guidelines given by the AQIA are used (Thomas and Scorgie, 2006) as indicated in Table 10.[11] Response to various pollutants is measured in terms of incident rates or risk factors (Van Horen, 1996; Sakulniyomporn *et al.,* 2011), where, for example, if the risk factor for mortality due to inhalation of specimen X is 3.3×10^{-6}, one person in 3.3×10^{-6} will die for every 1 μgm^{-3} increase in the concentration of specimen X.

3.4 Costs

By assigning a monetary value to the health costs, one is better able to compare the effects of different health impacts, which often have different units. Given its intangibility, valuing health impacts or health damage costs is complex (Sakulniyomporn *et al.,* 2011). Popular methods include the willingness-to-pay (WTP) and cost-of-illness (COI) approaches (Van Horen, 1996), as well as quality-adjusted life years (QALYs) and disability-adjusted life years (DALYs). A monetary value of the total impact is found by multiplying the number of cases by the unit cost of the specific case and summing over the range of chosen health outcomes.

As yet, unit health costs have not been identified for South Africa. Therefore, Hainoun *et al.* (2009) is followed. When costs are not readily available, the unit costs determined in other nations can be mul-

Table 9: Summary of incidence rates for selected health issues
Source: (a) Sakulniyomporn et al. (2011: 3476); (b) Thomas and Scorgie (2006: 2.16)

	Health endpoint	*Pollutant*	*Incident rate (case/person year μgm^{-3})*		
			Low	*Central*	*High*
Mortality [a]	Fatal cancer [b]	As	1.50E-03	3.30E-03	4.30E-03
	Fatal cancer [b]	Cr VI	1.10E-02	7.10E-02	1.50E-01
	Fatal cancer [b]	Pb	N/A	N/A	1.20E-05
	Fatal cancer [b]	Ni	2.40E-04	2.60E-04	3.80E-04
	Premature death	PM_{10}	4.52E-06	6.88E-06	9.30E-06
	Premature death	SO_2	4.40E-07	8.86E-06	1.74E-05
Morbidity [a]	CB in adults (≥25 years)	PM_{10}	1.30E-06	1.41E-05	2.79E-05
	RHA	PM_{10}	2.27E-05	4.54E-05	6.81E-05
	RHA	SO_2	N/A	1.26E-05	2.27E-05
	RHA	NO_2	N/A	N/A	2.02E-05
	CHA	PM_{10}	2.62E-05	4.72E-05	6.81E-05
	ERV	PM_{10}	1.12E-05	4.11E-05	7.48E-05
	AB in children (<25 years)	PM_{10}	1.94E-05	4.41E-05	7.23E-05
	ASA in children (<15 years)	PM_{10}	3.67E-04	5.98E-04	8.43E-04
	ASA in adults (≥15 years)	PM_{10}	4.26E-05	8.74E-05	1.32E-04
	RAD in children (≥18 years)	PM_{10}	2.90E-02	5.80E-02	9.10E-02
	ARS	PM_{10}	2.20E-01	3.00E-01	7.40E-01

Table 10: Summary of cancer incidence rates for selected compounds
Source: Thomas and Scorgie (2006: 2.16)

Compound	*Incident rate (case/person year μgm^{-3})*			*Cancer classification*	
	California EPA	*WHO Inhalation*	*US-EPA IRIS*	*IARC*	*US-EPA* [1]
Arsenic, inorganic	3.30E-03	1.50E-03	4.30E-03	1	A
Cadmium	4.20E-03	-	1.80E-03	2A	B1
Chromium VI, particulates	1.50E-01	1.1E-2 to 13E-2	1.20E-02	1	A
Lead	1.20E-05	-	-	2B	B2
Nickel and nickel compounds	2.60E-04	3.80E-04	2.40E-04	1	A
Nickel sulphate	4.90E-04	-	4.80E-04	1	A

Note:
1. Cancer classifications:
A: Human carcinogen
B: Probable human carcinogen. There are two sub-classifications:
  B1: Limited human data from epidemiological studies.
  B2: Sufficient evidence from animal studies and for which there is inadequate or no evidence from human epidemiological studies.
C: Possible human carcinogen.
D: Not classifiable as to human carcinogenicity.
E: Evidence of non-carcinogenicity for humans.

tiplied by the ratio of Purchasing Power Parity GNI (PPPGNI) between the two nations. This adjustment accounts for income differences, although it may not provide an exact health cost. Essentially, this is an application of the benefit transfer approach, and can provide a good estimate of the cost range.[12]

$$U_v^{SA} = U_v^R \times \left(\frac{PPP^{SA}}{PPP^R}\right)^{\gamma} \qquad (3)$$

U_V refers to the unit value in a specific country – *SA* for South Africa and *R* for a reference country – PPP is the gross national income (GNI) per capita adjusted for purchasing power parity and γ represents the income elasticity, set to 1. While the benefit transfer approach is a useful tool for determining costs where these would otherwise not be known, this methodology should not be seen as a valuation of a life – merely the potential lifetime income lost due to the death of an individual. Since income levels differ across countries, as shown in

Table 11, the income lost due to death (premature or otherwise) will also differ between countries. This is, however, no reflection on the relative importance of a life in one country compared to a life in another country. To adequately account for the full value of a life, albeit economic, social or otherwise, a multidisciplinary approach is required.[13]

Table 11: GNI per capita for selected regions and countries
Source: World Bank

Region	*GNI per capita (US$) 2010*
China	4 270
Germany	43 110
European Union	38 524
India	1 330
The Netherlands	49 050
South Africa	6 090
Sub-Saharan Africa	1 187
United Kingdom	38 370
United States	47 390
World	9 136

The health cost will be expressed in terms of cents per kWh (c/kWh) of electricity produced. Since no South African costs are available, the benefit transfer method is employed. Calculations of U_V for each disease is determined from United States (US) and Canadian studies. Equation (3) requires PPP values for South Africa, the US and Canada; 2010 PPP values are used, derived from World Bank data and expressed in terms of gross national income (GNI) based on PPP. The PPP values are given as $10 280, $47 020 and $38 310 for South Africa, the US and Canada, respectively. The Rand/US$ and Rand/C$ exchange rates for 2010 is quoted as the middle rate for 2010, as provided by the South African Reserve Bank (SARB) – R7.3222/1US$ and R7.1073/1C$. Mortality and morbidity costs given in Sakulniyomporn *et al.* (2011) and Büke and Köne (2010) are converted back to their original values, updated to 2010 values and used to calculate the unitary cost estimations for South Africa; see Table 12. In the case of lung cancer, costs are available for fatal and non-fatal cancers. This analysis gives the cost of all lung cancer cases in terms of fatal case costs, as this gives the maximum cost for a case of lung cancer.

4. Results

The incident rates give an indication of the marginal effect of ambient pollution on affected people. The calculation of the effect, *EFF*, is based on incident rates, population data and additional pollutant contributions from Kusile and equation (4), developed in Vrhovcak et al. (2005).

Table 12: The unitary costs of health impacts
Source: (a) Sakulniyomporn et al. (2011: 3476); (b) Büke & Köne (2010: 1–5)

Health endpoint	*Cost (R, 2010)*	*Estimation*
Mortality [a]		
Fatal cancer [b]	329 937 526	VOSL
Premature	15 630 357	WTP
Morbidity [a]		
CB in adults (≥25 years)	687 052	WTP
RHA	37 974	COI
CHA	4 066	COI
ERV	1 410	COI
AB in children (<25 years)	895	COI
ASA in children (<15 years)	99	COI
ASA in adults (≥15 years)	106	WTP
RAD in children (≥18 years)	168	WTP/COI
ARS	32	WTP

$$EFF = Conc \times Dens \times Area \times Rate \qquad (4)$$

Conc refers to the concentration of pollutants, *Density* and *Area* refer to the population density and surface area (m^2) of the area in question, and *Rate* refers to the incident rates. Cost calculations were done using the low, central and high estimates of the incident rates, while the actual costs are found by multiplying the cost for each impact by the corresponding number of cases and summing the costs.

The unit externality cost, expressed as c/kWh, is estimated and a summary of these findings is provided in Table 13. Based on this information, Kusile's localised health-related externality cost is estimated to be in the range of 0.09c/kWh to 6.08c/kWh, which compares well with the estimates of the studies depicted in Table 1. Differences are, however, expected as this study was confined to the GLC, whereas the other studies considered the entire national impact. This health cost represents an additional cost over and above the current electricity price of approximately 41c/kWh.

5. Discussion and conclusion

This analysis considers Kusile's air pollution health impacts. It does not consider OHS related costs associated with the operation of Kusile, because the necessary information is not yet available. Furthermore, although fly ash from ash dumps and coal storage piles contribute significantly to ambient PM concentrations, nothing is known about the characteristics of these ash dumps; therefore, health costs related to ash dumps are only partly incorporated by the inclusion of PM in the health cost.

While a large number of health impacts have been included, the list is by no means exhaustive. A

Table 13: The annual health cost associated with Kusile

Scenario	*0% Efficiency*			*90% Efficiency*		
Stack height	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*
Total cost (R m)	102.35–2 312.61	88.96–1 782.19	79.40–1 403.32	36.86–588.24	36.86–588.24	34.95–512.47
c/kWh	0.27–6.08	0.23–4.69	0.21–3.69	0.10–1.55	0.10–1.55	0.09–1.35

Table 14: The total annual health cost associated with Kusile for low, central and high incidence rates

	Scenario	*0% Efficiency*			*90% Efficiency*		
	Stack height	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*	*A1 (150m)*	*C1 (220m)*	*E1 (300m)*
Total cost (R million)							
GLC	Low	102.35	88.96	79.40	36.86	36.86	34.95
	Central	1 196.79	926.51	733.45	308.83	308.83	270.22
	High	2 312.61	1 782.19	1 403.32	588.24	588.24	512.47
Phola Low	Low	11.18	10.96	10.81	10.41	11.31	10.37
	Central	37.34	32.89	29.92	21.77	23.24	21.02
	High	65.37	56.64	50.81	34.81	37.01	33.35
Phola High	Low	55.23	54.13	53.40	51.38	55.88	51.19
	Central	186.01	163.77	148.94	108.16	115.55	104.45
	High	326.18	282.52	253.41	173.39	184.39	166.10
c/kWh							
GLC	Low	0.27	0.23	0.21	0.10	0.10	0.09
	Central	3.15	2.44	1.93	0.81	0.81	0.71
	High	6.08	4.69	3.69	1.55	1.55	1.35
Phola Low	Low	0.03	0.03	0.03	0.03	0.03	0.03
	Central	0.10	0.09	0.08	0.06	0.06	0.06
	High	0.17	0.15	0.13	0.09	0.10	0.09
Phola High	Low	0.15	0.14	0.14	0.14	0.15	0.13
	Central	0.49	0.43	0.39	0.28	0.30	0.27
	High	0.86	0.74	0.67	0.46	0.49	0.44

review of epidemiological literature does, however, suggest that a large proportion of the pollution-related causes of disease are included. While lung cancer has been included in the analysis, a future point of departure could be to include cancers of various natures into the cost structure.[14] Furthermore, this analysis does not consider the effect of pollution on foetuses. In a review of epidemiological research pertaining to the effects of air pollution on fetal health, Glinianaia *et al.* (2004) conclude that while the existence of causal associations between air pollution and fetal health outcomes is plausible – and despite a growing number of studies which focus on investigating this relationship – associations linking deteriorating fetal health and air pollution are weak. Once a clear relationship has been show between fetal health and air pollution, it is suggested that these health outcomes are also included in the analysis.

Presumably, ignoring these costs yields lower estimates for Kusile and their inclusion would likely increase the 0.09c/kWh to 6.08c/kWh range reported. Considerable data limitations prompted the use of benefit transfer techniques in order to find estimates of the costs. Once the plant is operational, the proxy data can be replaced with actual data to give a more accurate account of the health damage cost approach. Instead of localising the health cost by restricting the sphere of influence to the zone of maximum GLC, it may also be of value to consider the health costs associated with Kusile on a national, population-wide level. Such an analysis would, however, require more detailed information regarding the dispersion of Kusile's pollutants on a national level. Since Kusile is still in its construction phase, the available dispersion data dictated that only a localised cost calculation be conducted. Simple extrapolation of the data to a national context would not capture the complex dispersion of pollutants and would therefore not adequately – and realistically – reflect that dispersion of the pollutants contained in Kusile's emissions.

With any study making use of the data transfer method, there is the concern that the original data is not of good quality, or that it may be biased in some way (Boyle and Bergstrom, 1992). Using data from an EIA heighten those concerns, since the EIA is commissioned by a party that may be interested in the project. Unfortunately, a quantitative assessment of the quality of the EIA cannot be done. Instead, it is common practice for the EIA to be subjected to extensive rounds of public and private input, as well as an independent review of the document. The draft EIA was subjected to public scrutiny (Ninham Shand, 2007) and only the potential effect or the air quality on poultry in the region was questioned. This concern was addressed in the final EIA. Furthermore, an independent review of the IEA (Mark Wood Consultants, 2007) concluded that '…the specialist studies are generally well prepared, are clear and provide the necessary basis for an objective evaluation of the overall impact of the project.' Lastly, no major issues were identified in the AQIA documentation. While not guaranteeing the EIA is wholly objective and reliable, the EIA numbers are the only numbers available. However, it should be noted that any errors or omissions in the EIA data will be carried over into this analysis, due to the transfer methodology applied.

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Notes

1. Each of the new plants – Kusile and Medupi – is projected to generate 4 800 MW of electricity and require 17 million tons of coal annually (AfDB, 2009; Eskom, 2011; Synergistics, 2011).
2. PM is typically classified into one of three fractions: PM2.5, PM10 and PM > PM10; particles with diameter less than 2.5 μm, less than 10μm or greater than 10μm, respectively.
3. Occupational health and safety (OHS) issues also arise when considering the health impacts of electricity generation cycle. For example, links between electromagnetic fields and leukemia have been uncovered (Theriault et al. 1994). Some studies related to health and mining have also been undertaken (van Horen, 1996; Ross and Murray, 2004; Hermanus, 2007); however, there are no available studies associating PM or other pollutants to workplace accidents, so OHS will not be considered further.
4. Schuman and Cavanagh (1982), measuring abatement costs, and Hohmeyer (1988), applying the top-down approach, are worth noting for being the first of their type. Unfortunately, not all of the data limitations noted in their studies have since been alleviated.
5. South African reliance on coal as a source of power dates back to 1870, when it was first used in a Kimberley diamond mine.
6. Given its abundance, it comes as no surprise that coal is South Africa's main source of energy, providing over 70% of the country's primary energy and 93% of its electricity (Department of Energy, 2010).
7. Carbon monoxide, radionuclides and heavy metals are also likely to impact health. Similarly, there are some indirect externalities related to greenhouse gas emissions, but the effect of climate change on human health is primarily global (Hainoun et al., 2009); therefore, these effects fall outside the scope of this study.
8. The EIA considered numerous sites – sites X and Y (Figure 2) emerging as the most preferred; site X was finally selected.
9. Data availability and quality necessitates the use of only the most common health impacts associated with air pollution and their corresponding pollutants. Particles with diameter smaller than 2.5 μm (PM2,5) are included in the broader PM10 definition, and therefore, are not included in the cost analysis to avoid double-counting.
10. The potential health impacts for various heavy metals were also considered in the EIA. Cancer risk, due to heavy metal inhalation, ranged between 1:45million and 1:10million (Ninham Shand, 2007). For mercury, specifically, the highest annual, highest daily and annual average concentrations did not exceed the most stringent of international health standards (Ninham Shand, 2007). Therefore the health cost associated with heavy metal exposure will not significantly contribute to the overall health cost to society of coal-fired electricity generation by the Kusile plant.
11. To provide central, low and high estimates for the incidence rates of lung cancer, the three sets of guidelines given in Table 10 were ranked in order from lowest to highest and assigned to the three categories.
12. Although extending the analysis to make use of the entire income distribution would provide estimates of health impact equity, the necessary data is not available for the sites considered in this analysis.
13. Such an estimation falls beyond the scope of this study.
14. Research on the relationship and causality between ambient pollution levels and the prevalence of certain cancers have yet to give conclusive results and can therefore not be included in the analysis.

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