Determination of regional emission factors for the power sector in Southern Africa

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Abstract
The generation of power within Southern Africa is reviewed. A study is described in which the emission factors for CO_2 and NO_x were determined experimentally across a wide range of power stations and technologies, and compared to the IPCC default factors. It was found that the CO_2 emission factors tended to be at the upper end of the IPCC default range, whereas the NOx emission factors were generally below the low end. The results from South Africa tend to dominate the regional picture at present, but this is likely to change in the near future, as Botswana has announced plans to introduce over 4 000 MWe of coal-fired power stations.

Keywords: SADC, climate change, power sector, emission factor, greenhouse gas

Introduction

The assessment of the impact of greenhouse gases on the environment requires a reasonably accurate assessment of the quantities of greenhouse gases being emitted into the atmosphere from various sources. The reliability of such emission estimates depends on the accuracy of both the activity data and emission factors. The Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006) identifies three approaches to estimation:

- Tier 1 – using the quantity of fuel employed and a default emission factor for the source category;
- Tier 2 – using the quantity of fuel combusted and a country-specific emission factor for the source category and fuel for each gas;
- Tier 3 – as Tier 2 but using technology-specific emission factors for the source category and fuel for each gas.

The purpose of this study was therefore to develop country-specific emission factors, which would also allow comparison with the default factors employed by the IPCC. Many the national inventories for Sub-Saharan Africa, including that for the power sector, have been based on the previous (1996) default emission factors (IPCC, 1996). The study was initiated in 2002. The project was supported under Eskom's Southern Africa Climate Change Research Initiative, launched in 1999, which has the following objectives:

- To provide assistance to the Southern African Development Community (SADC) countries and power utilities within those countries to meet their obligations in terms of the United Nations Framework Convention for Climate Change;
- To ensure compatibility of regional efforts to address economic growth and achieve sustainable development, while addressing the requirements of the United Nations Framework Convention for Climate Change;
- To analyze the potential risks to regional utilities under the threat of a climate change response, and to develop adaptation measures to offset such risks;
- To map out cleaner power sector alternatives in anticipation of any international policy to reduce the dependence on greenhouse gas emitting fossil fuels like coal, which is the dominant primary energy resource used for power generation in the SADC region; and
- To be ready for business opportunities, which may present themselves under the Kyoto Protocol flexible mechanisms such as the Clean Development Mechanism (CDM).

The emphasis of this research project was on carbon dioxide (CO_2), which is the key greenhouse gas that is mandatory for the preparation of National Communications and CDM baselines. Emission factors for oxides of nitrogen (NO_x), emission factors from coal, diesel power plant combustion as well as methane (CH_4) from coal mining were also determined. Emission factors are expressed as kg emissions/per energy unit of fuel (fuel-based) and kg emissions/unit of electrical energy generated (plant/energy based).

Other objectives of the project included:

- Systemizing power sector data and knowledge on regional power sector characteristics;
- Capacity building in the region for climate change research, development of a national greenhouse gas inventory and the successful formulation of CDM type projects;
- The establishment of capacity for continued improvements of emission factors in the SADC region;
- The building of capacity and creation of interest within regional utilities in plant data and emission management;
- The development of an organizational model for improving emission factors that could be applied in other sectors and regions.
- The building of a network for climate change research institutions in the region; and
- Contributions to the IPCC emission factor database.

Overview of power generation in the SADC

The SADC region is supplied by 42.5 GW of thermal power, 6.5GW of hydropower and 1.8 GW of nuclear power (Kritzinger-van Niekerk et al, 2002). The regional electricity supply is dominated by thermal generation (79.9%) with 77.7% being derived from coal-fired power plants (Kritzinger-van Niekerk and Moreira, 2002).

South Africa is the dominant producer, with 42.9GW of capacity (Eskom, 2006). It obtains 94.1% of its generation capacity from coal and the remainder from nuclear (4.3%), and diesel (1.5%) (Digest of South African Energy Statistics 2005). Other countries, where thermal generation capacity makes a significant proportion of the national power capacity include Botswana 132 MW (100%) (Mbendi, 2007) and Zimbabwe 1295 MW (61%) (Mbendi, 2007). Botswana has announced plans to increase its coal-fired generation by over 3 700 MW, primarily for export (Fossil Fuel Foundation, 2008). Namibia has the 120 MW Van Eck thermal power station, the 320 MW Ruacana hydroelectric station, and the 24 MW Paratus diesel plant, but the thermal stations are primarily for standby capacity. The transmission grid is linked to the South African and Zambian grids. Production in 2000 totalled 30 million kWh, of which 2% was from fossil fuels and 98% from hydropower. Over half the electricity was exported (Nationsencyclopedia, 2007)

It is clear that coal-fired thermal plants are dominant in those countries where the fuel is locally available i.e. in South Africa, Botswana and Zimbabwe. The capacities of utility owned coal-fired power stations range from 6 MW to over 3840 MW.

Most of the diesel power stations considered in the study have capacities ranging from 20 kW to 10 MW and generally supply isolated demand centres remote from the national grid. Some of these diesel plants comprise standby generators, which provide backup when there is an outage on the grid.

The gas turbines in operation in the region are usually somewhat larger than diesel plants, with a range of 3 MW to 180 MW, the larger units being operated in South Africa (171 MW), Angola (93 MW), Mozambique (79 MW), and Tanzania (18.5 MW) (Southern Centre, 1998). The use of gas for power generation in the region is currently limited but is likely to increase in countries with natural gas reserves that include Angola, Mozambique, Namibia and South Africa. 2 GW of additional capacity is being installed in South Africa (Eskom, 2006).

There are also a number of countries with significant proportion of hydro-generation capacity, namely the Democratic Republic of Congo (DRC) (99%), Mozambique (95%), Zambia (93%), and Tanzania (83%). The sources of energy in the SADC are summarised in Table 1.

Outline of study

The study was carried out on coal-fired and diesel stations, in South Africa (coal), Tanzania (coal and diesel), Zambia (diesel), Zimbabwe (coal), Botswana (coal), Namibia (diesel) and Mozambique (diesel). The prevalence of coal mining in the region also called for an attempt to estimate coal-mining methane emission factors.

The study was undertaken in three phases between 2002 and 2005. Under Phase 1, project teams in South Africa, Tanzania, Zambia and Zimbabwe undertook an inventory of thermal power plants characteristics with regard to age, capacity, technology, and operating conditions; followed by the determination of emission factors based on the IPCC (IPCC, 1996) methodology and Fenger et al. (1990). To determine country/regional fuel based emission factors using these methods, data on fuel consumption, carbon content and heat value of the fuels were required. Phase 1 therefore also involved the collection of data on fuel consumption and corresponding electricity generation in order to verify plant efficiencies.

Phase 2 involved determinations of CO_2 and NOx for coal-fired and diesel plants based on flue gas measurements. A methane emission factor from underground mining in Zimbabwe was determined from secondary data on methane concentrations monitored at the Hwange coal mine in Zimbabwe. Phase 3 continued on the same measurements as in Phase 2 with an additional measurement made in Namibia (diesel), Botswana (coal) and Mozambique (diesel). For Mozambique, the fuel based emission factor was assumed to be similar to that of diesel used in the region (e.g. Zambia) and the plant based emission factor was then derived using the plant efficiency.

The names and fuel types of the coal-fired and diesel power stations covered in the research are given in Table 2.

Under Phase 1, data collection was undertaken for all of the 11 large coal-fired power stations (1900 MW to 3840 MW) in South Africa, 4 medium coal-fired power stations in Zimbabwe (120 MW to 920 MW) and one small coal-fired power station (6 MW) in Tanzania. For diesel plants, data was collected for 11 diesel power stations (0.5 MW to 3.5 MW) in Zambia, and a suite of 7 diesel (1 MW to 8 MW), 2-jet fuel (15 MW to 40 MW) and 2 petrol (1 MW to 8 MW) power stations in Tanzania.

In Phase 2, flue gases were measured at Kendal (3840 MW), Lethabo (3558 MW) and Arnot (1980 MW) power stations in South Africa, at Bulawayo (120 MW), Harare (135 MW) and Hwange (920 MW) power stations in Zimbabwe, at Kiwira power station (6 MW) in Tanzania and at Morupule power station (132 MW) in Botswana. At the time of measurements, coal quality and plant efficiencies were noted.

Similar measurements were undertaken for diesel plants at Kaoma (3467 kW) and Luangwa (540 kW) in Zambia. In Tanzania, measurements were undertaken at Kigoma (4.08 MW), Mtwara (4.94 MW), Njombe (1.28 MW) and Songea. In Namibia, emission factors were determined at

Table 1: Electricity generation mix in Southern African countries (MWe)
Source: www.sapp.co.zw and links

Country	*Max. demand*	*Coal*	*Diesel*	*Gas*	*Hydro*	*Nuclear*	*Total capacity*
Angola	397		135		610		745
Botswana	434	132					132
Lesotho	90				72		72
Malawi	242				285		285
Mozambique	285		127		2385		2512
Namibia	491	120	24		149		293
South Africa	33461	39863	296	342	600	1840	42941
Swaziland	172	10			41		51
Tanzania	509		80		561		641
Zambia	1330		125		1716		1841
Zimbabwe	2066	1225			750		1975
DRC	1012		38		2404		2442
TOTAL	40489	41350	825	342	9573	1840	53930

Table 2: Characteristics of power stations studied

Country	*Power stations*	*Fuel type*	*Technology*	*Capacity (MW)*	*Load factor*	*Thermal efficiency*
South Africa	Arnot	Coal	PF-Tangential firing	3 450	66%	35%
	Lethabo	Coal	PF-Wall Firing	3 558	62%	35%
	Kendal	Coal	PF-Tangential firing	3 840	63%	34%
	Matimba	Coal	PF-Tangential firing	3 690	75%	34%
	Duvha	Coal	PF-Wall Firing	3 450	66%	35%
	Tutuka	Coal	PF-Wall Firing	3 510	56%	35%
	Matla	Coal	PF-Wall Firing	3 450	63%	35%
	Majuba-wet	Coal	PF-Wall Firing	2 007	63%	34%
	Majuba-Dry	Coal	PF-Wall Firing	1 836	39%	32%
	Kriel	Coal	PF-Wall Firing	2 850	64%	35%
	Hendrina	Coal	PF-Wall Firing	1 900	66%	32%
Tanzania	Kiwira	Coal	Chain grate	6		12%
	Kigoma	Diesel		4.08		30%
	Mtwara	Diesel		4.94		34%
	Njombe	Diesel		1.28		32%
	Songea	Diesel		2.42		39%
Zimbabwe	Hwange	Coal	PF 4x120MW			
2x220MW	920	65%	31.8%			
	Harare 3	Coal	PF 2x30MW	60	17%	20.1%
	Harare 2	Coal	Chain grate 2x7.5,			
10, and 20MW	75	17%	20.1%			
	Munyati	Coal	Chain grate 5x20			
MW, 2x10MW	120	17%	20%			
	Bulawayo	Coal	Chain grate 3x30			
MW, 2x15MW	120	17%	19.3%			
Botswana	Morupule	Coal	Chain grate, 4x33MW	132	85%	31.6%
Zambia	Lukulu	Diesel		0.540		21%
		Diesel		1.130		23%
	Kasempa	Diesel		0.795		34%
	Kabompo	Diesel		0.750		35%
	Mwinilunga	Diesel		0.750		39%
		Diesel		0.790		36%
	Zambezi	Diesel		0.750		36%
	Mufumbwe	Diesel		0.640		28%
	Kaoma	Diesel		1.067		31%
		Diesel		2.400		29%
	Kaputa	Diesel		0.795		24%
	Luangwa	Diesel		0.540		19%
	Chama	Diesel		0.528		8%
Mozambique	Massingir	Diesel		0.296	60%	30%
Namibia	Paratus	Diesel		24		32.9%

Paratus diesel power station (24 MW) in Walvis Bay. In Mozambique, emission factors were determined for Massingir diesel power station (296 kW). The flue gas measurements for coal-fired power stations resulted in emission factors for CO_2 and NO_x, while results for diesel plants were only for CO_2.

It should be noted that while the above has concentrated on the installed capacity, account must also be taken of the load factors in determining the total annual emissions. In this study, however, the accent was on the emission factors themselves, so the results are expressed in terms of emissions per MW electrical.

A Lancom III portable flue gas analyzer, with the

Table 3: Coal qualities studied

Country	*Power station*	*C%*	*N%*	*Ash%*	*GCV (MJ/kg)*	*NCV (MJ/kg)*	*Type*
South Africa	Kendal	51.7	1.12	27.8	19.9	19.8	Bit
	Kendal	52.5	1.14	26.8	20.2	20.1	Bit
	Lethabo	40.3	0.82	37.2	14.9	14.8	Sub Bit
	Arnot	57.2	1.42	20.9	22.8	21.5	Bit
Tanzania	Kiwira	51.0	1.15	26.5	18.5	17.8	Sub Bit
Zimbabwe	Bulawayo	76.5	1.72	14.6	29.9	28.4	Bit
	Harare	76.5	1.72	14.6	29.9	28.4	Bit
	Hwange	68.3	1.88	24.7	24.2	22.9	Sub Bit
Botswana	Morupule	63.9	1.4	18.7	24.0	22.7	Sub Bit

GCV – Gross calorific value; NCV – Net calorific value, Bit – bituminous coal; Sub Bit – Sub bituminous coals

Table 4: Comparison of Zambian diesel with IPCC default composition

Parameter	IPCC Default	Country specific	Difference	Percentage difference
Net calorific value (GJ/tonne)	43.33	43.06	0.27	0.62%
Density (kg/m^3)	0.840 (Standard value)	0.82 – 0.86 (Average used 0.845)	0.005	0.60%
Carbon content	0.87-0.90* (Average = 0.885)	0.90**	0.015	1.67%
Carbon oxidized	0.99	0.99 (assumed)	–	–

** Typical values of most diesel fuels based on different chemical formulation*

*** Value based on Zambia's diesel chemical formulation of $C_{14}H_{18}$*

capability to monitor up to 9 gases and including data acquisition and analysis software, was used to measure flue gas emissions from power plants in Phase 2 and Phase 3. The Lancom III is capable of measuring any of these nine gases: CO low, CO high, O_2, NO, NO_2, NO_x, SO_2, H2S, CO_2 and hydrocarbons if the relevant sensors are employed. For this project, four sensors capable of detecting CO_2, CO, NO_x and O_2 were purchased with the instrument. In addition, the analyzer can calculate combustion efficiency, excess air, and can provide measurement corrections such as oxygen normalization, wet or dry analysis and automatic reading conversions. The instrument measures volumetric concentrations of gases. The installed sensors are calibrated with their respective calibration gases prior to measurement, and checked after the measurement. The instrument was rotated among the project teams in the participating countries.

Results

Fuel characteristics

Coal qualities

The region uses a variety of coal types as depicted in Table 3. The coals used in South Africa have carbon content ranging from 40.3% to 57.2% (ultimate analysis), net calorific value from 14.8 MJ/kg to 21.5 MJ/kg and ash content from 20.9% to 37.09%. These fuel qualities are so varied that using a uniform IPCC default value as an emission factor for all the countries would not be justified.

Diesel quality

Qualities of diesel were analysed for Zambia and the results show that there is very little difference from the international diesel properties assumed for the IPCC default values (Table 4), hence the energy-based emission factors for Phase 1 were derived using the IPCC default value for diesel power plants. This confirms the International Energy Agency (IEA) assertion, that there is little difference between gas oils from country to country, unlike coal properties (IEA, 2001).

Fuel based emission factors

Table 5 gives the emission factors for CO2 as determined by default methods in Phase 1 and as measured in Phase 2. It also gives the NO_x emission factors for coal fired plants. The various measurements of diesel emissions were consistent within each country but differed from country to country, so only the averages for each country are given. NO_x emissions were not measured on diesel plants.

Table 5: Emission factors from Southern African power stations based on fuel energy

		Phase 1		*Phases 2 and 3*	
Country	*Plant Name*	*CO_2 (kg/GJ)*	*NOx (kg/GJ)*	*CO_2 (kg/GJ)*	*NOx (kg/GJ)*
South Africa	Kendal 2005 repeat	94.6 (89.5-99.7)*	1.5 (0.5-5)*	96.3 97.4	0.446 0.21
	Lethabo	94.6 (89.5-99.7)	1.5 (0.5-5)	99.6	0.583
	Arnot	96.1 (92.8-100)	1.5 (0.5-5)	95.3	0.28
Tanzania	Kiwira	96.1 (92.8-100)	1.5 (0.5-5)	73	0.125
	Diesel	74.1 (72.6-74.8)	0.6 (0.2–2)	73.9	
Zimbabwe	Bulawayo	94.6 (89.5-99.7)	1.5 (0.5-5)	97.5	0.07
	Harare	94.6 (89.5-99.7)	1.5 (0.5-5)	97.3	2.48
	Hwange	96.1 (92.8-100)	1.5 (0.5-5)	97.1	0.29
Botswana	Morupule	96.1 (92.8-100)	1.5 (0.5-5)	103.0	0.32
Mozambique	Diesel	74.1 (72.6-74.8)	0.6 (0.2–2)	74.2	
Namibia	Diesel	74.1 (72.6-74.8)	0.6 (0.2–2)	74.8	
Zambia	Diesel	74.1 (72.6-74.8)	0.6 (0.2–2)	74.4	

** Values in brackets represent the minimum and maximum values (IPCC 2006).*

Table 6: Emission factors for Southern African power plant based on electrical production

		Phase 1	*Phases 2 and 3*	
Country	*Plant Name*	*CO_2 (kg/MWh)*	*CO_2 (kg/MWh)*	*no (kg/MWh)*
South Africa	Kendal	978	972	4.15
	Lethabo	890	1027	7.50
	Arnot	952	1082	3.30
Tanzania	Kiwira	2810	2330	
	Kigama	870	858	
	Mtuara	867	869	
	Njambo	856	858	
	Sonqua	910	-	
Zimbabwe	Bulawayo	1792	1450	
	Harare	1693	1520	
	Hwange	1071	1160	
Botswana	Morupule	1153	1168	
Mozambique	Massinqir	876	890	
Namibia	Paratus	807	819	
Zambia	Koama	974	865	
	Luanqua	1493	1339	

Emission factors on a basis of power produced

Table 6 gives these emission factors. In this case, some individual diesel-powered stations were identified. There were few reports of NO_x emissions on the basis of power produced.

Emission factors for methane from coal mining

The emission factor for the fugitive CH_4 from underground coal mining at Hwange in Zimbabwe was found to range from 4.3 to $10m^3$ CH_4/ton of coal. The emission factor for underground coal mining in South Africa was $0.5m^3$ CH_4/ton coal (Lloyd & Cook, 2005). These are generally below the IPCC default values of 10m3 to $25m^3$ CH_4 per ton of coal.

Discussion

Comparison of the Phase 1 and Phase 2 emission factors given in Tables 5 and 6 shows that:

- The IPCC default factors based on fuel energy represent the South African power plants reasonably well, considering in particular the relatively high ash content of some of the coal. However, when the comparison was on the basis of sent-out energy, the default methods were seriously in error. In part, this was the result of the lower-than-normal efficiency caused by the use of high-ash coal.

- The default factors based on fuel energy were reasonably satisfactory for all other plants except for two. At the Tanzanian Kiwira plant, the very low load factor is believed to be the cause of the relatively low emission factor. At the Botswana Morupule plant, the low efficiency is probably the result of employing an old technology.
- The default factors based on power produced were somewhat less than those measured, except for the Tanzanian and Zambian coal plants. In the latter two cases, the emission factors were so high that they could reasonably be described as likely to lie outside the range of any correlations on which the default factors had been based.
- There was excellent agreement between the measured and default factors for all diesel plants studied.
- The NOx data was fairly limited, but in all but two cases the measured values were below the lowest of the IPCC's default values.

The derived national and regional fuel based emission factors for coal-fired stations are given in Table 7. These were derived using a weighted average of fuel based emission factors of the power stations in the region based on generation capacity. It is clear that, due to significance of the South African coal-fired generation capacity, the regional fuel-based emission factor is largely influenced by that for South Africa.

Table 7: Country-wide and regional emission factors for coal-fired stations based on fuel consumed

Country	*CO_2 (kg/GJ)*	*NOx (kg/GJ)*
South Africa	96.4	0.35
Tanzania	73	0.13
Zimbabwe	97.2	0.33
Botswana	103	0.32
Region	96.5	0.35

This situation is, however, likely to change in the near future. Botswana is building about 3600 MW of new coal-fired electrical generation and the Morupule Power Station is to undergo a 600 MW expansion (de Beer, 2007). This means that Botswana will be in a position to contribute nearly 4 000 MW to the Southern African Power Pool, and regional emission factors will change as a result of the reduction in the relative strength of the South African supply.

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