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The environmental costs of platinum–PGM mining and sustainability: Is the glass half-full or half-empty?

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ABSTRACT

The growing popularity of platinum group metals (or PGMs, including platinum and palladium) for a wide range of applications leads to some interesting issues for mining and sustainability. The uses of PGMs includes catalytic converters for air pollution control in vehicles, growing jewellery use, catalysts for various purposes (especially petroleum and chemicals processing), hydrogen fuel cells, and many others. Given the growing importance of most of these PGM uses in more sustainable technologies or in making industrial processes more efficient, it is critical to understand the complex sustainability issues which surround PGMs. At present, South Africa is the dominant PGMs producer and holds ~88% of estimated global resources, with additional production and resources in Russia, Zimbabwe, Canada and the United States. Given the concentrated location of PGM resources, what are the likely trends in PGM mining with respect to environmental sustainability? That is, what are the costs in terms of energy, pollution, greenhouse gas emissions, water, land use impacts, social impacts, economic aspects associated with this globally important industry? This paper compiles and analyses a range of data on PGM mining. It synthesizes a unique combination of data which relates typical production aspects such as ore grade and scale with sustainability aspects such as greenhouse, energy and water costs. The findings are critical in understanding the debate about the increasing environmental and social costs of some materials and technologies which are considered crucial for sustainable technologies based on PGMs. Overall, the paper represents a valuable insight into the environmental and resource sustainability of the PGM sector.

1. Introduction

Platinum group metals (PGMs) possess a range of unique chemical and physical properties and are increasingly finding important uses in a wide variety of environmentally-related technologies. The use of PGMs consists of catalysts for chemical process facilities (especially oil refineries), catalytic converters for exhaust control in transport vehicles, hydrogen fuel cells, electronic components, and a variety of specialty medical uses, amongst others. Given the need to expand almost all of these uses to meet environmental challenges, demand growth for PGMs can reasonably be expected to be sustained long into the future.

The global production of PGMs is dominated by South Africa due to their large economic PGM resources in the Bushveld Complex, while other countries such as Russia, Canada, Zimbabwe, and the United States play a minor but important role. Concerns are being raised, however, about the long term ability to supply PGMs to meet future technological needs (e.g. Gordon et al., 2006), as well as allegations of significant environmental and social impacts such as water pollution, unfair village relocation, economic disparity and compensation issues (amongst others) (Curtis, 2008; Rajak, 2008; Mnwana and Akpan, 2009).

This paper presents a detailed review of the PGM industry and major environmental costs such as water, energy and greenhouse gas emissions (GGEs), focusing primarily on South Africa as a case study. A range of data are compiled, including annual production statistics, major inputs and outputs, and analysed with respect to unit efficiencies or 'sustainability metrics'. The relationships between production statistics and sustainability metrics are then investigated with a view to understanding the current trends in PGM mining and potential future implications. Although social impacts are crucial in sustainability, they are outside the scope of this paper. The paper presents a unique case study for a group of metals which are uniquely concentrated in one major region of the earth and pose some intriguing and difficult sustainability issues for the future.

2. Review of platinum–PGM mining and processing

The platinum group is made up of six closely related metals with similar physical and chemical properties (Vermaak, 1995).

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They are divided according to their densities into a heavier category, comprising platinum (Pt), iridium (Ir) and osmium (Os), and a lighter group, consisting of palladium (Pd), rhodium (Rh), and ruthenium (Ru). Due to their high corrosion and oxidation resistance, along with Au and silver, PGMs are classified as noble metals. In addition, the relatively low average concentration and overall scarcity of PGMs in the earth's crust leads to them being considered as precious metals. Common abbreviations used are '4E' which includes Pt, Pd, Rh and Au (3E + Au), while 6E includes Pt, Pd, Rh, Ru, Ir and Au (5E + Au).

In 2007, global PGM production was 509 t, consisting of 165.8 t Pt and 86.5 Pd from South Africa, 27 t Pt and 96.8 t Pd from Russia, 6.2 t Pt and 10.5 t Pd from Canada, 5.3 t Pt and 4.2 t Pd from Zimbabwe and 3.9 t Pt and 12.8 t Pd from the United States (Loferski, 2008). Historical production and price is shown in Fig. 1, with 2007 production and economic resources given in Table 1. The PGMs are one of the few metals which have stayed relatively constant in their real price over time (Kelly and Matos, 2009), despite strong production growth since 1960.

2.1. Platinum–PGM mining and processing

There are broadly considered to be four main types of economic PGM ores (Vermaak, 1995; Cabri, 2002):

- Stratiform deposits – where PGMs occur in large Precambrian mafic to ultramafic layered intrusions. The major examples include the Merensky and Upper Group 2 (UG2) Reefs of the Bushveld Complex, South Africa, the Great Dyke in Zimbabwe and the Stillwater complex in Montana, United States. These deposits are usually considered primary due to their size (~10–1000 Mt) and grade (3–10 g/t PGMs, ~0.2–1% Ni + Cu).
- Norite intrusions – where meteoritic impact is considered to have been instrumental in allowing PGM emplacement. The major example is the Sudbury Irruptive complex in Ontario, Canada (~10–1000 Mt, 1–3 g/t PGMs, ~2–3% Ni + Cu).
- Ni–Cu bearing sills – related to rift structures, allowing concordant intrusive sheets. The best known examples are the Nor'ilsk-Talnakh District in Russia and the Jinchuan deposits in China (~10–1000 Mt, 2–15 g/t PGMs, ~3–5% Ni + Cu).

Table 1
PGM production and resources in 2007 by country (Loferski, 2008; USGS, 2009).

Country	Production			Reserves[b]	Reserve base[b]
	t Pt	t Pd	t PGM	t PGM	t PGM
South Africa	165.83	86.46	310.92	63,000	70,000
Russia	27.00	96.80	138.30	6200	6600
Canada	6.20	10.50	20.20	310	390
Zimbabwe	5.30	4.20	11.00	–	–
United States	3.86	12.80	–	900	2000
Columbia	1.40	–	–	–	–
Australia	~0.90[a]	~0.73[a]	–	–	–
World	212	219	509	71,000	80,000

[a] Assuming Australia is credited for PGMs extracted from ores and concentrates exported to Japan.
[b] See USGS (2009) for detailed definitions, but they are broadly similar to reserves and resources as used in Australia, Canada, South Africa and elsewhere.

- Placer deposits – alluvial sedimentary deposits containing coarse PGMs (commonly Pt) were mined in conjunction with alluvial Au for some 2000 years prior to the 20th century. Columbia has long been a major source of alluvial-derived Pt, producing about 1.4 t Pt in 2007 (the major placer source).

The mining of PGM ores is through conventional underground or open cut techniques. The next stage is grinding and gravity-based (or dense media) separation, followed by flotation to produce a PGM-rich concentrate. The run-of-mine ore grades are typically several g/t, while concentrates are some hundreds of g/t (Vermaak, 1995). Concentrate is then smelted to produce a PGM-rich Ni–Cu matte, with the PGMs extracted and purified at a precious metals refinery (including Ni–Cu by-products). The processing is therefore more analogous to base metals rather than Au, which relies on cyanide leaching and hydrometallurgy. Smelting of concentrates from Ni–Cu mining can also be a moderate source of PGMs (e.g. Russia, Canada). Further details on PGM ore processing are given by Vermaak (1995) and Cabri (2002).

2.2. The Bushveld Complex, South Africa

The North West province of South Africa hosts the Bushveld Complex, a large igneous complex about 370 km east–west and

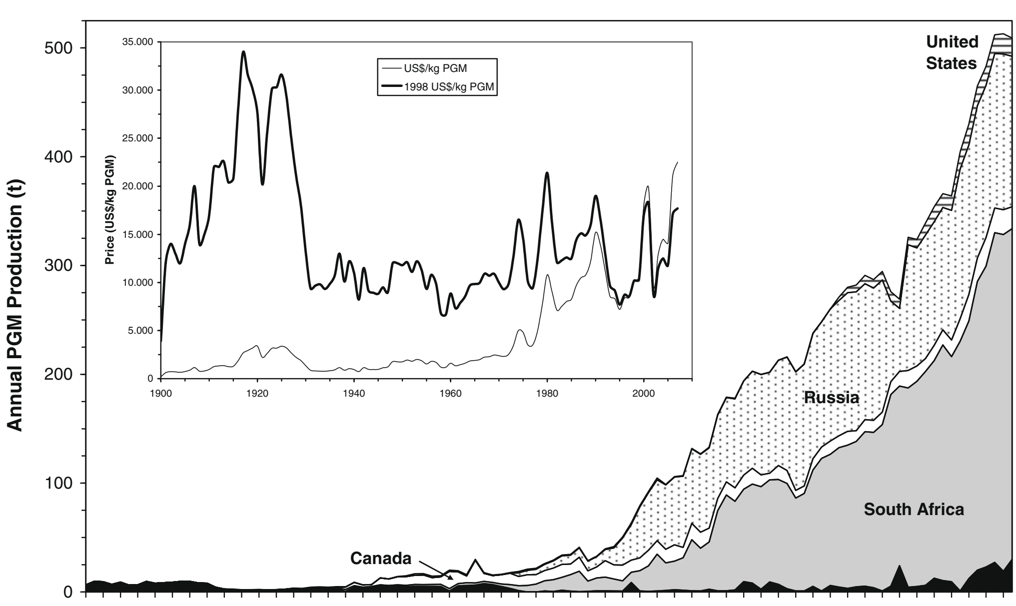

Fig. 1. Historical PGM production and price (inset) (data combined from Vermaak, 1995; Loferski, 2008; CMSA, 2008; Kelly and Matos, 2009; NRC, 1944–2008; SADME, 2007).

up to 240 km north–south (Vermaak, 1995). It consists of multiple mafic layers formed during the intrusion of the Bushveld granites, giving rise to stratiform reefs up to 1.4 km in total thickness and 9 km in depth. Due to cover by younger sediments, outcrop of the Bushveld Complex occurs in two bracket-like lobes on the west and east side plus a linear lobe to the north. A regional and geological map and cross-section are given in Fig. 2. Further details on the geology are given by Vermaak (1995) and Cawthorn et al. (2002).

The presence of Pt in the goldfields around Johannesburg was well established by the end of the nineteenth century, mainly as a scientific curiosity. In 1906 chemist William Bettel reported that he discovered Pt 'in situ' from what is now considered to be the Bushveld Complex (Cawthorn, 2006). This discovery sparked two decades of exploration and research, based largely on comparison to Russian Pt occurrences in chromitite-rich regions. In 1924, geologist Hans Merensky followed up on a sample sent to him from a Bushveld farmer, Andries Lombaard, and confirmed it was coarse Pt and therefore potentially economic (Cawthorn, 2006). This source, found throughout the Bushveld Complex, is called the Merensky Reef. The original chromitite mineralisation noted by Bettel in 1906 is called the Upper Group 2 (UG2) Chromitite Reef.

The northern limb of the Bushveld Complex contains the Platreef, which was at the centre of unprofitable and short-lived Pt mining during the late 1920s. Anglo Platinum developed the first commercial Platreef mine at Potgietersrust in 1993 (now called Mogalakwena). The Platreef is a focus for exploration, however the economic mineralisation of the Platreef and its relationship to the rest of the Bushveld Complex are still poorly understood (Kinnaird et al., 2005).

Both the Merensky and UG2 reefs are remarkably continuous over tens to hundreds of kilometres, with the PGMs mineralogically associated with base metal sulfides (Vermaak, 1995). The very thin nature of the Merensky and UG2 reefs (~1 m) requires narrow mining techniques. Although earlier mines were based largely on the Merensky Reef, the UG2 Reef is now increasingly being mined and processed. The Platreef is slightly thicker (~4 m) and is mined by open cut at Potgietersrust due to the shallower reef depth. Depth of underground mines can range from 100 to 2000 m, with most presently active at several hundred metres deep.

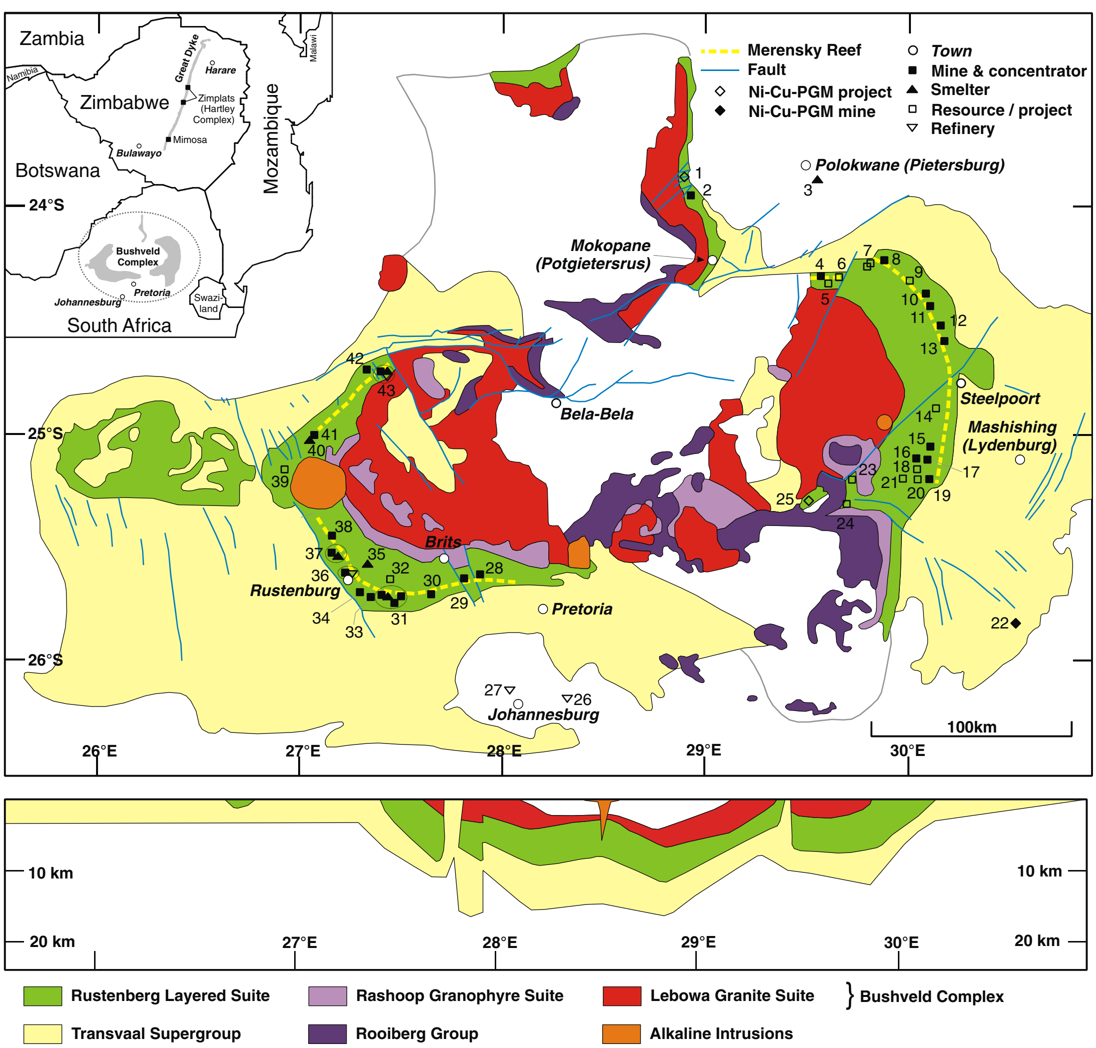

Fig. 2. Southern Africa and Bushveld Complex geological map (top) and conceptual cross-section (bottom), including PGM mines, smelters, refineries and future projects (main map adapted from Scoates and Friedman, 2008, and various company reports). Names: 1 Boikantsho, 2 Potgietersrust (Mogalakwena), 3 Polokwane, 4 Limpopo, 5 Mphahlele, 6 Bakgaga, 7 Tigerpoort-Leeuwkop, 8 Lebowa, 9 Ga-Phasha, 10 Twickenham, 11 Marula, 12 Smokey Hills, 13 Modikwa, 14 Kennedy's Vale, 15, Two Rivers, 16 Mototolo, 17 Everest North, 18 Der Brochen, 19 Everest, 20 Booysendal, 21 Marreesburg, 22 Nkomati, 23 Blue Ridge, 24 Loskop, 25 Sheba's Ridge, 26 Impala Springs, 27 Lonmin, 28 Elandsfontein, 29 Crocodile River, 30 Pandora, 31 Lonmin (Marikana) Group, 32 Leeuwkop (Afplats), 33 Marikana Joint Venture, 34 Kroondal, 35 Waterval, 36 Rustenberg, 37 Impala Group, 38 Bafokeng-Rasimone, 39 Pilanesberg, 40 Mortimer, 41 Union, 42 Amandelbult, 45 Northam.

A statistical summary of South African, Zimbabwean and other PGM mines is given in Table 2, with major Ni–Cu mines which produce PGMs summarised in Table 3. A compilation of economic resources reported by companies is shown in Table 4.

2.3. PGM demand and uses

The uses for PGMs are wide and varied. Platinum's most common uses are in catalytic converters for exhaust control in transport vehicles (~50%), jewellery (~30%), and minor uses spread across chemicals, electrical components, glass, financial investment and petroleum process catalysts, shown in Fig. 3. Demand for PGMs in catalytic converters is showing strong growth in recent years, nearly tripling since 1990. The introduction of fuel cell technologies in hydrogen applications and vehicles could be another major demand for PGMs in the medium to long term.

3. Quantifying the environmental sustainability of PGMs

In the past decade, there has been a strong growth in annual environmental or sustainability reporting by numerous mining companies (Mudd, 2007, 2008, 2009a), including many South African and especially PGM companies. In general, sustainability reports cover the environmental, economic and social performance of a company alongside statutory financial reporting. The compilation and analysis of the reported data can provide critical insights into a given mining sector, as well as valuable data for broader analyses of other mineral commodities. This section briefly describes the sustainability context and challenges for mining, and outlines the methodology adopted in this study.

3.1. Sustainability and mining

At first glance, applying the principles of sustainability to mining is seemingly a simple oxymoron – since mining means to extract a resource which is finite and 'non-renewable'. The nature of mining is therefore widely considered to be unsustainable, since it is depleting a stock (or 'natural capital'). The paradox, however, is that the global mining industry is now larger than ever in history, producing minerals and metals at a rate which dwarf's previous generations of mines (Mudd, 2009b).

While there is evidence to suggest that many mineral commodities have shown growth in known economic resources over recent decades in some countries (e.g. Australia; Mudd, 2009b), as growing demand has encouraged exploration, technology and price – it is increasingly clear that the historical patterns of mineral resources and development cannot simply be assumed to continue unaltered into the future. The primary constraints may vary from social and governance issues in one region, to water or energy resources in another, or GGEs globally.

With respect to mining, the application of sustainability principles is therefore complex. The global mining industry, as part of their contribution to the Johannesburg Earth Summit in 2002, released a major report on mining and sustainability. The 'Mining, Minerals and Sustainable Development' (MMSD) report (IIED and WBCSD, 2002) was a major shift from arguing the historical case of growing resources over time due to exploration, technology and prices, to a position where mining can contribute to sustainable development (even if a mining project is only a relatively short term endeavour).

A common approach to sustainability is ensuring the ability of current generations to meet their needs without compromising the ability of future generations to meet their needs (i.e. the Brundtland definition; see IIED and WBCSD, 2002). In the context of mining, this can be taken to include the availability of resources and a productive environment at former mining or milling sites. The context for sustainable development and mining can therefore be taken back to first principles as balancing the potential environmental, social and economic risks. Further discussion of sustainability and mining are given in Mudd (2007, 2009b).

3.2. Sustainability reporting

An increasingly popular way of demonstrating performance against sustainability objectives is through sustainability reporting. This involves reporting and discussing all aspects of

Table 2
Recent average production of South African, Zimbabwean and other PGM projects.

Company	Project and mine type	Mt ore/yr	4Eg/t	t Pt	t Pd	t Rh	t Au	t PGM^{6E}
AngloPt$^{50\%}$–Bafokeng$^{50\%}$	Bafokeng–Rasimone (UG)	2.518	4.36	5.834	2.393	0.384	0.349	9.359
AngloPt$^{100\%}$	Lebowa (UG)	1.509	4.54	3.112	2.095	0.323	0.176	6.158
AngloPt$^{100\%}$	Potgietersrust (OC)	4.830	3.62	5.670	5.952	0.385	0.630	12.416
AngloPt$^{100\%}$	Amandelbult (UG)	6.602	5.46	18.584	8.504	2.134	0.612	32.974
AngloPt$^{100\%}$	Rustenburg (UG)	11.457	4.26	25.161	12.164	2.810	1.116	44.971
AngloPt$^{85\%}$	Union (UG)	5.717	3.79	9.656	4.307	1.503	0.167	18.020
AngloPt$^{100\%}$	Twickenham (UG)	0.142	4.77	0.259	0.262	0.043	0.008	0.618
AngloPt$^{50\%}$–Xstrata$^{37\%}$	Mototolo JV (UG)	1.314	3.46	1.918	1.133	0.283	0.027	3.850
AquaPtt$^{100\%}$	Everest (UG$^{70.2\%}$)	1.988	2.96	2.539	1.355	0.411	0.039	5.212
AquaPt$^{50\%}$–AngloPt$^{50\%}$	KroondalJV(UG$^{93.7\%}$)	4.843	3.62	6.042	2.887	1.056	0.049	15.158
AquaPt$^{50\%}$–AngloPt$^{50\%}$	MarikanaJV(OC$^{77.8\%}$)	1.490	4.30	1.836	0.787	0.249	0.023	4.149
AfrRainMin $^{41.5\%}$–AngloPt$^{50\%}$	ModikwaJV(UG$^{93.3\%}$)	2.408	4.11	4.012	3.941	0.821	0.116	–
AfrRainMin $^{55\%}$–Implats $^{45\%}$	Two Rivers (UG)	2.205	4.11	2.901	1.662	0.476	0.039	6.074
Lonmin $^{82\%}$–Incwala Res $^{18\%}$	Marikana(UG$^{87.2\%}$)	13.237	4.88	25.10	11.31	3.299	0.612	44.109
Lonmin$^{100\%}$	Limpopo (UG)	0.608	3.74					
Lonmin $^{42.5\%}$–AngloPt$^{42.5\%}$	Pandora JV(OC$^{62.7\%}$)	0.523	5.06					
AquaPt$^{50\%}$–Impala$^{50\%}$	Mimosa (UG$^{98.2\%}$)	1.406	3.67	2.028	1.512	0.159	0.272	5.010
Impala$^{86.5\%}$	Implats (UG$^{96.0\%}$)	15.593	4.84	33.03	15.022	3.839	–	60.059
Impala$^{86.9\%}$	Zimplats(OC$^{73.4\%}$)	2.059	3.49	2.776	2.315	0.250	–	6.015
EastPlats$^{85\%}$	Crocodile River (UG)	0.844	4.66	1.026	0.455	0.162	0.019	2.021
Impala$^{73\%}$	Manila (UG)	1.043	3.88	1.360	1.384	0.285		3.573
Northam$^{100\%}$	Northam (UG)	1.993	5.57	6.041	2.880	0.599	0.207	11.009
Norilsk Nickel$^{100\%}$	Stillwater, USA (UG)	1.068	19.39	3.919	13.17	–	–	–
North American Palladium $^{100\%}$	Lac des Iles,Canada (OC)	4.770	2.17^{Pd}	0.666	7.347	–	0.589	–
	Totals	**94.90**	**4.41**	**164.1**	**110.2**	**19.47**	**5.63**	**290.8**

Sources: Anglo Platinum (AP, var); Aquarius Platinum (AqP, var); AfrRainMin – African Rainbow Minerals (ARM, var); Implats/Impala (Impala, var.); Lonmin (var.); EastPlats (EP, var.); Northam (var.); Norilsk (var.); North American Palladium (NAP, var.); Stillwater (SMC, var.); Anglo American (AA, var.); $^{xyz\%}$ denotes %ownership.

Table 3
Statistical overview of Ni–Cu–PGM projects (recent average production) (ARM, var.; Norilsk, var.; Inco, var.; VI, var.).

Company	Project	Type	Mt ore/yr	%Ni	%Cu	PGM g/t	kt Ni	kt Cu	t Pt	t Pd
Norilsk Nickel	Taimyr, Russia	UG/OC	14.517	1.65	2.87	9.30	123.7	350.9	23.13	96.89
Vale Inco	Sudbury, Canada	UG/OC	7.805	1.36	1.46	~2.5	90.66	111.4	4.871	6.018
African Rainbow Minerals[50%]	Nkomati, South Africa	OC	0.490	1.36	~0.8		5.26	3.01	1.40 (t PGMs)	

Table 4
Total attributable company reserves and resources of PGM projects by ore type (2007 data).

	Reef	Mt ore	4E g/t	t PGM (4E)
Anglo Platinum	Merensky	1466.6	5.27	7729
Anglo Platinum	UG2	2889.2	5.05	14,590
Anglo Platinum	Platreef	2793.7	2.18	6090
Anglo Platinum	Tailings	190.0	1.02	194
Northam Platinum	Merensky	383.5	4.90	1879
Northam Platinum	UG2	582.9	4.39	2559
Aquarius Platinum	Great Dyke	45.8	3.82	175
Aquarius Platinum	UG2	85.8	4.52	388
African Rainbow Minerals	Merensky	102.7	2.83	291
African Rainbow Minerals	UG2	116.1	5.36	622
Impala Platinum	Merensky	501.7	5.50	2759
Impala Platinum	UG2	909.2	5.74	5219
Impala Platinum	Great Dyke	2023.3	3.65	7385
Impala Platinum	Tailings	48.1	0.42	20
Lonmin	Merensky	348.6	4.60	1604
Lonmin	UG2	531.3	4.84	2571
Lonmin	Platreef	269.7	3.46	933
Eastplats	UG2	209.3	4.50	942
Platinum Australia	UG2	5.5	5.60	31
Platmin	Merensky[a]	148.7[a]	3.59[a]	534[a]
Sub-total	Merensky	2952	5.01	14,796
Sub-total	UG2	5329	5.05	26,922
Sub-total	Platreef	3063	2.29	7023
Sub-total	Great Dyke	2069	3.65	7560
Sub-total	Tailings	238	0.90	214
Subdury (Canada)	Ni–Cu–PGMs	160.3	2.0	321
Taimyr (Russia)	Ni–Cu–PGMs	2216	5.04	11,169
Stillwater (USA)	PGMs	40.0	16.4	656
	Total	**16,068**	**4.27**	**68,661**

Sources: AA (var.), AP (var.), AqP (var.), ARM (var.), Impala (var.), Lonmin (var.), EP (var.), Northam (var.), Norilsk (var.), NAP (var.), Inco (var.), Vale Inco (var.), PA (var.), Platmin (2008).
[a] Platmin do not report ore types separately for reserves and resources, with the Merensky Reef being the main ore type (Platmin, 2008).

performance for a given year, covering social, economic and environmental aspects. Some mining companies, such as WMC Resources Ltd. (now part of BHP Billiton Ltd.) and Placer Dome Ltd. (now part of Barrick Gold Corporation), began releasing annual environmental reports in the mid-1990s and these evolved into broader sustainability reports by 2000. Since the 2002 Johannesburg Earth Summit and the release of the MMSD report, numerous mining companies now report sustainability alongside statutory financial performance.

Early methods for reporting used internal company schemes. Due to the need to ensure consistency across companies, industry sectors or other organisations, the Global Reporting Initiative (GRI) was established in 1997 to develop protocols and promote and enhance sustainability reporting. The third edition was released in 2006 (GRI, 2006), with a pilot mining sector supplement in 2005 and the final draft mining sector supplement in early 2009 (GRI, 2009). The GRI protocol is now the most common sustainability reporting tool used by mining companies (Mudd, 2009a).

The GRI itself is voluntary, and can be applied in whole or in part. There are five main sections of reporting, including economic, environmental, labour practices, human rights and social aspects. The qualitative and quantitative indicators used for each area are either core or voluntary.

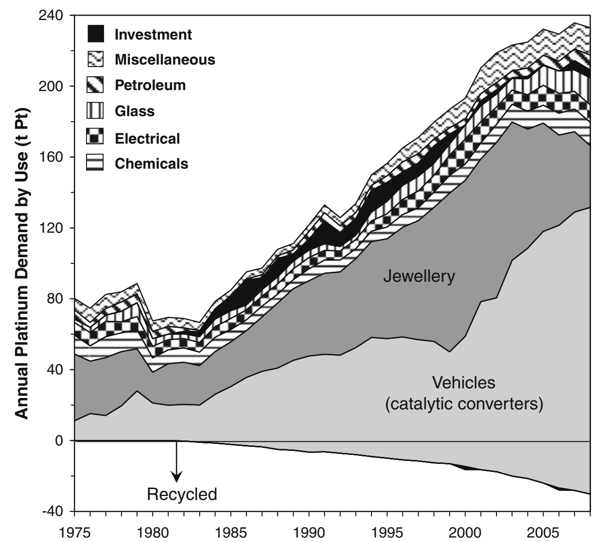

Fig. 3. Pt demand by use, 1975–2008 (JM, 2009).

The principal core environmental indicators of relevance to mining used in this study are:

- EN3/EN4 – direct/indirect energy consumption by primary energy source;
- EN8 – total water withdrawal by source;
- EN16 – total direct and indirect greenhouse gas emissions by weight;
- EN21 – total water discharge by quality and destination;
- EN22 – total weight of waste by type and disposal method.

Voluntary environmental indicators of relevance to mining used in this study are:

- EN9 – Water sources significantly affected by withdrawal of water;
- EN10 – Percentage and total volume of water recycled and reused.

Based on the final draft mining sector supplement (GRI, 2009), large volume mine wastes, such as tailings and waste rock, only need to be discussed with respect to site-specific environmental risks and it is not core to report annual tonnages – although 'hazardous' mine wastes should be reported.

Overall, the emergence and continuing improvement in sustainability reporting is providing a valuable source to assess the environmental sustainability aspects of mining. PGM companies in South Africa are certainly at the forefront in this regard, with Anglo Platinum perhaps showing the best quality reporting of data and analysis (Mudd, 2009a) (though some issues are contested or remain a work in progress; e.g. Curtis, 2008).

3.3. Quantifying sustainability and PGMs production

The availability of growing data sets on wastes, energy, water and greenhouse gas emissions from sustainability reporting can be easily combined with normal production statistics from financial performance. In this way it is possible to link aspects such as energy, greenhouse and water costs with ore grade, annual throughput or project configuration, providing some useful benchmarks to compare individual site operations but also understand the environmental implications as PGM production continues to grow to meet rising demand.

In this study, we will focus primarily on South African PGM projects, with some data from Zimbabwean projects. The 'sustainability metrics' we use are unit consumption per PGM production (e.g. GJ/kg PGM, m^3/kg PGM) with respect to ore grade (4E g/t), unit consumption per tonne of ore milled (e.g. m^3/t ore, GJ/t ore) with respect to mill throughput (Mt ore/year), and similarly for GGEs (e.g. t CO_{2-e}/kg PGM, t CO_{2-e}/t ore).

3.4. Projecting future production and sustainability constraints

In addition to analysing unit sustainability metrics, this study also combines these with past production trends to project possible future scenarios for GGEs. This allows comparison to proposed targets for reductions in GGEs, and therefore gives a useful target for individual projects. Since there is no extensive historical data set for production available (beyond the ~10 years for this study), ore grade is assumed to be constant over time (see discussion below) and total GGEs calculated from production and unit GGEs. In addition, a 'Hubbert'-style peak curve is developed to assess whether PGMs can be considered to fit this approach (based on methods in Cavallo, 2004).

4. Results

The reported sustainability metrics are separated into projects (or groups) for which data is reported for a mine plus concentrator only versus those which include a mine, concentrator and smelter. Summary data for all mines and projects is given in Table 5.

4.1. PGMs production

The reporting of production statistics is reasonably consistent between PGM companies, such as ore grade as 4E g/t, individual PGM production (Pt, Pd, Rh, Au, sometimes Ru and Ir) and economic resources. Recent ore grades for major PGM companies are shown in Fig. 4, showing a gradual decline for all plotted, especially Anglo Platinum. Based on current economic resources (Table 4), it can be expected that ore grades will stabilise and remain in the range of 3–5 g/t for most companies (assuming that current mining techniques and the primary focus on Merensky-UG2 ore continues). In the early 1990s the extent of UG2 ore was ~30% (Vermaak, 1995), while the ore mix is now ~65% UG2, ~26% Merensky and ~9% Platreef (see Table 2).

4.2. Water consumption

The graphs of unit water costs versus throughput or over time, shown in Fig. 5, do not show strong evidence of water efficiency gains for most projects. That is, larger project scale does not lead to higher water efficiency, a common belief for larger project scales. Ore grade does not appear to be a factor in unit water efficiency. Over time, most projects have shown somewhat stagnant water efficiency, with only Lebowa showing strong reductions in total water consumption and unit water costs over time, which also appear to be sustained. Some projects are showing the reverse, however, such as Northam with significantly increasing water costs over time.

4.3. Energy consumption

The various graphs in Fig. 6 show no substantive evidence for improved unit energy efficiency at higher throughputs, a common belief for larger project scales. There does appear to be a minor negative scale effect for unit energy consumption for stand alone mine-concentrator-smelter projects with low throughputs (i.e.

Table 5
Summary of environmental sustainability metrics by PGM mine/project or group.

Individual project/Mine	Mining	Milling	Energy	Energy	Water	Water	CO_{2-e} Emissions
	MJ/t rock	MJ/t ore	GJ/kg PGM	MJ/t ore	m^3/kg PGM	m^3/t ore	t CO_{2-e}/kg PGM
Bafokeng–Rasimone (MC)	239 (2)	154 (2)	116 (7)	409 (7)	235 (7)	0.828 (7)	29.1 (7)
Lebowa (MC)	404 (2)	153 (2)	164 (7)	606 (7)	385 (7)	1.397 (7)	39.4 (7)
Potgietersrust (MC)	21 (2)	232 (2)	201 (7)	500 (7)	277 (7)	0.695 (7)	31.1 (7)
Amandelbult (MC)	292 (2)	148 (2)	106 (7)	465 (7)	209 (7)	0.928 (7)	26.3 (7)
Rustenburg (MC)	295 (2)	160 (2)	132 (7)	475 (7)	229 (7)	0.828 (7)	33.2 (7)
Union (MC)	324 (2)	130 (2)	190 (7)	521 (7)	237 (7)	0.660 (7)	42.9 (7)
Twickenham (MC)	80 (1)	–	28.5 (1)	107 (1)	409 (2)	1.626 (2)	2.3 (1)
Mototolo JV (MC)	–	170 (2)	74.8 (2)	196 (2)	192 (2)	0.509 (2)	18.6 (2)
Mimosa (MC)	–	–	107 (3)	305 (3)	579 (3)	1.640 (3)	–
Manila (MC)	–	–	108 (3)	393 (3)	582 (3)	2.155 (3)	–
Crocodile River (MC)	–	–	145 (1)	310 (1)	1086 (1)	2.328 (1)	33.6 (1)
Northam (MCS)[a]	1268 (4)	487 (4)	226 (4)	1755 (4)	1612 (4)	12.6 (4)	78.3 (1)
Zimplats (MCS)	–	–	241 (3)	710 (3)	606 (3)	1.760 (3)	–
	Energy	Fraction					
Company/Group Totals	Direct	Indirect	GJ/kg PGM	MJ/t ore	m^3/kg PGM	m^3/t ore	t $CO_{2\text{-}e}$/kg PGM
Implats (MCS)	37.2% (5)	62.8% (5)	254.6 (5)	962.3 (5)	544.2 (2)	1.998 (2)	50 (5)
Lonmin (MCS)	20.1% (4)	79.1% (4)	167.6 (6)	469.3 (6)	272.5 (6)	0.768 (6)	39.5 (6)
Northam (MCS)	7.9% (4)	92.1% (4)	–	–	–	–	–
Anglo Platinum (MCS)	23.6% (4)	76.4% (4)	–	–	–	–	–
	Energy	Fraction					
Company/Group Totals	Mining	Milling	Smelting	Refining	Other		
Anglo Platinum (MCS)	41.0% (4)	23.5% (4)	25.7% (4)	3.5% (4)	6.3% (4)		

Note: MC – mine and concentrator; MCS – mine, concentrator and smelter; number of years of data in brackets. *Sources*: AA (var.), AP (var.), AqP (var.), ARM (var.), Impala (var.), Lonmin (var.), EP (var.), Northam (var.).
[a] Assuming coal is used in milling/smelting only and diesel is used in mining only.

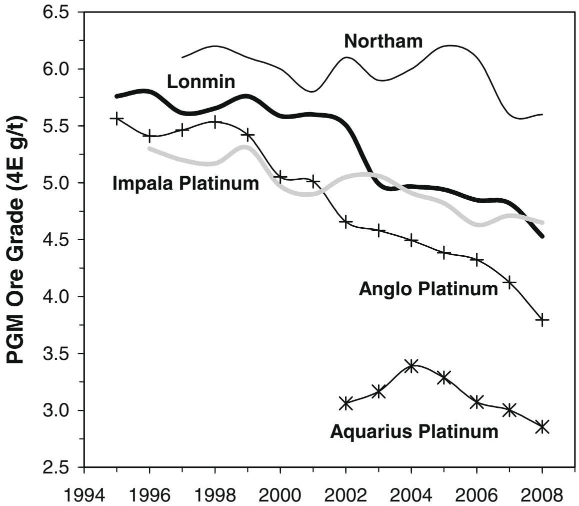

Fig. 4. Ore grades over time for selected PGM companies.

lower scales entail higher costs). Ore grade does appear to be significant for unit energy consumption (correlation coefficient 51.9%, Fig. 6). No project studied has shown long term energy efficiency improvements over time, with most showing relatively stable trends. The Lebowa and Northam projects, however, show substantive increases in energy costs over the past few years – despite both maintaining similar production levels and ore grades.

The low energy cost for mining at Potgietersrust (21 MJ/t rock) is due to this being an open cut mine, while the deep Northam underground mine (~2 km) has the highest mining energy consumption (1244 MJ/t rock). The data in Table 5 also shows that indirect energy (electricity) is generally the dominant energy input overall, with the majority of energy being used by underground mining. This would be due to the narrow mining techniques used, requiring large areas of development for small returns in ore compared to bulk mining techniques. Although a relatively small percentage of Bushveld ore is derived from open cut mines, many PGM producers have planned expansions to incorporate open cut mines in the future. Comparison of underground mines to the open cut Potgietersrust mine shows that there is a trade off between high energy underground mining versus low energy open cut mining (i.e. MJ/t rock) and the amount of solid wastes produced, since open cut mining produces large volumes of waste rock (see later section).

4.4. Greenhouse gas emissions

A moderate relationship is suggested between ore grade and unit GGEs (correlation coefficient 38.1%, Fig. 7), while the correlation between unit energy and unit emissions, surprisingly, only yields a correlation coefficient of 63.4% (Fig. 8) – despite South Africa's electricity supply being dominated by coal (89.7%) with a small proportion of hydro-electricity (5.0%) (Eskom, 2009). The variability could be due to different estimation methods used by

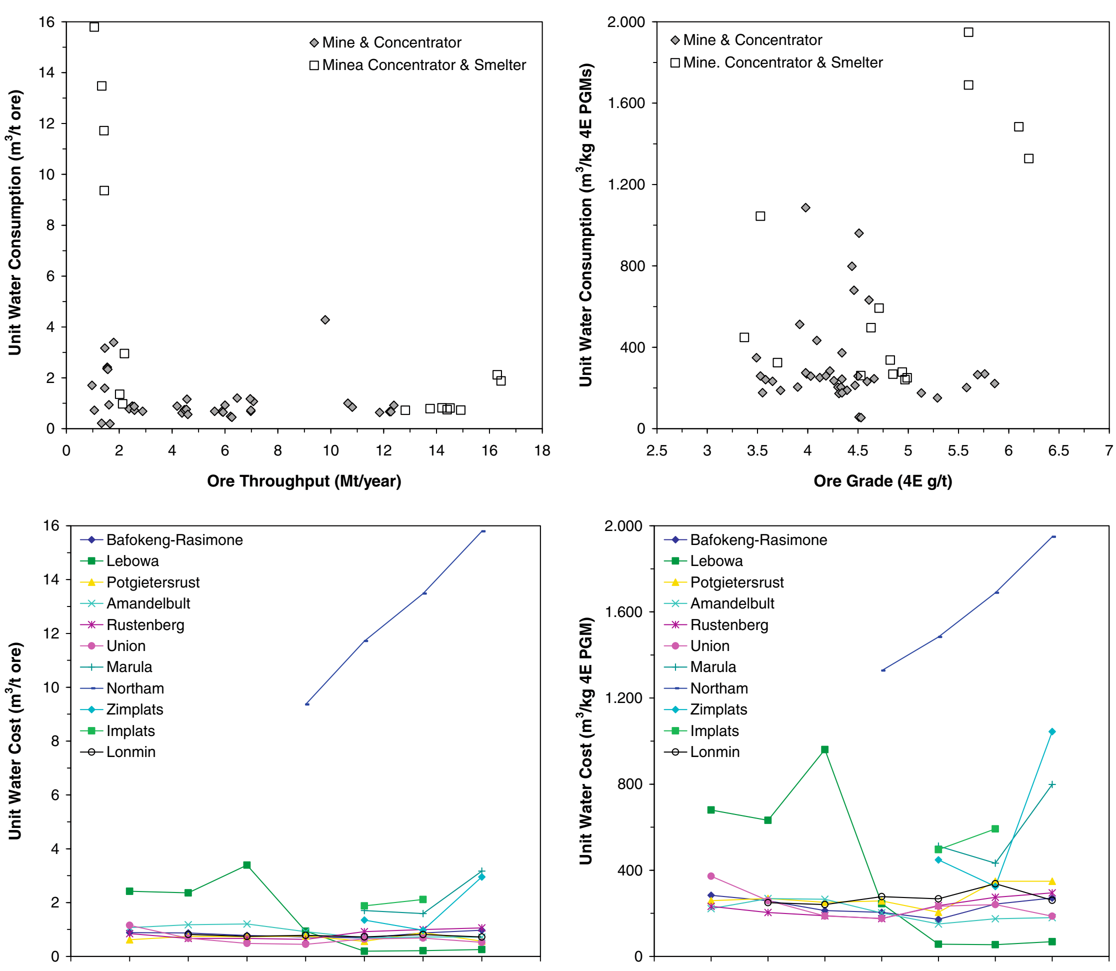

Fig. 5. Unit water consumption versus ore throughput (top left) and ore grade (top right), and unit water consumption over time versus ore throughput (bottom left) and ore grade (bottom right).

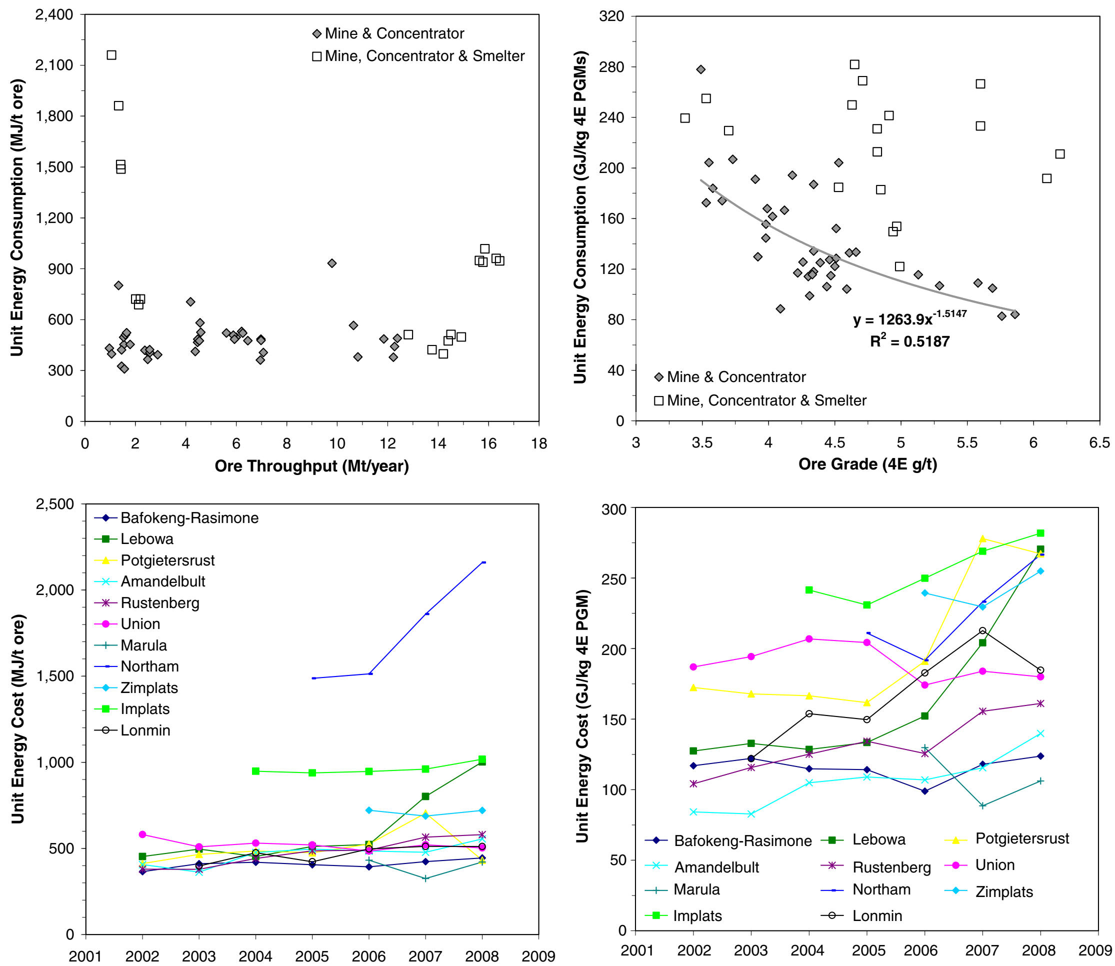

Fig. 6. Unit energy consumption versus ore throughput (top left) and ore grade (top right), and unit energy consumption over time versus ore throughput (bottom left) and ore grade (bottom right).

companies, although given the dominance of electricity this would not expected to be the case. Most of the values which appear to be outliers are the Northam project, which is one of the deepest PGM mines (at ~2 km) on the Bushveld and is a smaller scale, stand alone project (mine, mill, smelter and refinery). Unit GGEs over time show a slight but gradually increasing trend for all projects included in Fig. 8.

Since there is some evidence for major PGM producers showing declining ore grades over the past decade (Fig. 4), the implication is that unit GGEs could begin to increase if no action is taken. It is worth noting that some companies are now responsible for GGEs of the order of several millions of tonnes per year – and if development and production continues to grow similar to historical rates, this will lead to major increases in total emissions.

Based on the data in Fig. 7 and Table 5, the GGEs growth due to production increases is likely to be much greater than possible savings due to mine/mill/smelter efficiency improvements. To date, it would appear that the energy savings achieved at most sites are relatively modest or cancelled out by other factors such as operational issues (e.g. South African electricity crisis). For example, some Anglo Platinum mines show variation within a typical range (e.g. Bafokeng, Union), while others show a gradual increase over time (e.g. Lebowa, Potgietersrust, Amandelbult, Rustenburg). In other words, if production doubles there is little evidence that existing mines can reduce energy consumption by half. This means that GGEs will become an increasingly important issue as PGM production continues to grow.

4.5. Solid wastes – waste rock and tailings

The majority of PGM ore is sourced by underground mining, with 2007 production data showing that for the Bushveld, Great Dyke and Stillwater underground mining represents 88.6% of the ore milled, with 11.4% by open cut mining. Given that some small underground mines are missing in Table 2, the proportion of underground mining would be slightly higher.

There are two large volume wastes which need to be considered in mining – tailings (solid waste remaining after metal extraction) and waste rock (rock excavated during mining but with no economic metals). Both types of wastes require active planning and management to prevent major environmental or social impacts such as tailings dam failures (e.g. 1974 Bafokeng tailings disaster; Van Niekirk and Viljoen, 2005), acid mine drainage or other problems (e.g. dust, environmental health issues). In addition, slag wastes from smelters are important (and can even be reprocessed to extract residual PGMs), and are commonly disposed of in tailings dams at PGM mines.

Given that the ratio of ore to concentrate is typically around 30–50:1, this means that some 96–98% of the ore becomes tailings. For mining, waste rock to ore ratios are typically much greater than unity for open cut mining (e.g. 5–20:1) and the reverse for underground mining. At present, there is no data available on underground waste rock generation in the Bushveld or other mines, but could be expected to be around 1–5:10. The waste:ore ratios reported for the Potgietersrust, Kroondal and Marikana Joint

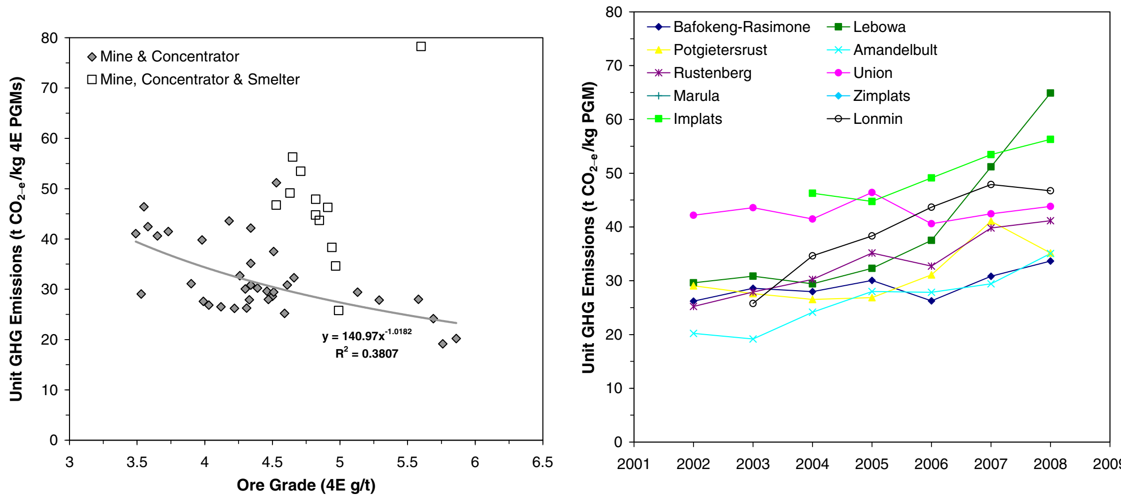

Fig. 7. Unit greenhouse gas (GHG) emissions versus ore grade (left) and over time (right).

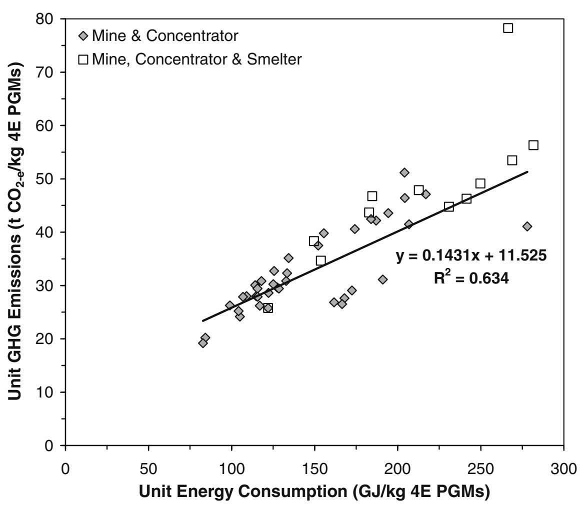

Fig. 8. Unit energy costs versus unit greenhouse gas emissions.

Venture open cut mines range from 6.9 to 23.7:1, leading to waste rock ranging from 2.6 to 94.6 Mt/year.

At present, it is rare for companies to report total mine wastes under their control and active management. One exception, however, is Anglo Platinum, reporting in 2008 that their cumulative mine wastes were 730.8 Mt of tailings and 665.4 Mt of waste rock (AP, var.) – demonstrating the large scale and significance of managing these wastes in the surface environment long into the future.

Studies by Anglo Platinum (AP, var.) suggest that both Merensky and UG2 tailings have a low acid mine drainage potential, although potential drainage waters from tailings would still be high in sulfate – meaning tailings still require active environmental management to prevent impacts on water resources. Anglo Platinum claim that there are no impacts on water sources or related ecosystems or habitats directly related to their operations (2008 sustainability report) (AP, var.). However, this claim is contested by ActionAid (Curtis, 2008), who argue that there is evidence for local impacts on water resources used by surrounding communities of some Anglo Platinum operations (especially Potgietersrust). This example highlights the importance of pro-active management of large tonnage mine wastes, especially bordering large local communities which depend on water resources adjacent to mining projects.

4.6. Projecting future production and greenhouse gas emissions

A 'peak' curve was developed from historical production, with the estimated total resource being cumulative production to 2007 and reserves or reserves plus reserves base (see Table 1). From this, a further projection was derived assuming a unit GGEs factor of 39.4 t CO_{2-e}/kg PGM (the production-weighted average from Tables 2 and 5). The modelled curves are given in Fig. 9, with correlation coefficients for the two peak models of annual production being 98.1% and 97.5% for reserves or reserves plus reserves base, respectively. Under both models the peak of production is significantly higher than present, with reserves giving a peak of 1251 t PGMs in 2037 and reserves plus reserves base a peak of 2451 t PGMs in 2049 (similar to current Au production). For GGEs, peak emissions are 49.3 Mt CO_{2-e}/year and 96.6 Mt CO_{2-e}/year, respectively. Adopting the unit metric of 39.4 t CO_{2-e}/kg PGM for 2007 gives about 25 Mt CO_{2-e}/year – showing that the increase in production will lead to considerable increases in GGEs over the same period in which the world is aiming to reduce emissions by some 50% or more.

While it is important to recognise that resource and environmental factors are possible constraints on future PGM production, it is also important to note that the rate of PGMs production growth may also be constrained by demand. During the past decade the demand for Pt has on many occasions outweighed supply. If Pt demand increases due to commercial scale adoption of PGM technologies (e.g. fuel cells), the longevity of PGM resources could be affected. Long term growth rates have been high, however, suggesting that in the short term, production will not be constrained by the amount of the resource but principally by demand and economic issues (including substitution, such as cheaper Pd for Pt). In the longer term, production is more likely to be constrained by environmental issues rather than demand, and potentially social issues (e.g. South Africa). Another factor which is not captured by the peak curve is recycling (Fig. 3), which has been gradually increasing but still only represents a minor portion of PGM use.

5. Discussion: the environmental costs and future of PGMs

The compiled data underpins a range of issues with respect to PGM production into the future, centred around the longevity of known resources, resource consumption and environmental impacts.

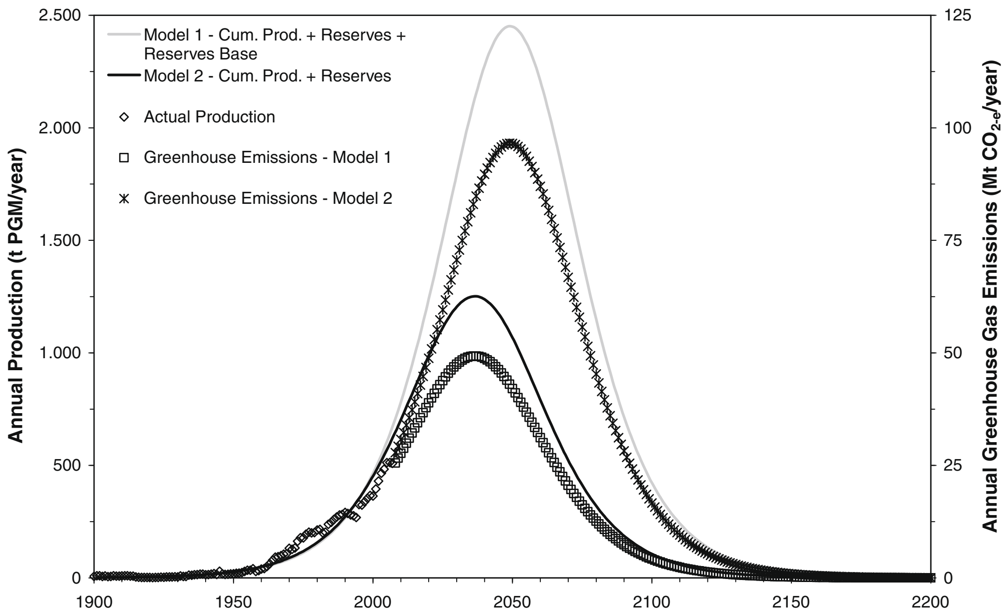

Fig. 9. Peak PGM production curves and projected greenhouse gas emissions.

The presently known economic reserves of 71,000 t PGMs compare to 2007 production of 509 t PGMs and cumulative production from 1900 to 2007 of 12,431 t PGMs. A further 80,000 t PGMs is estimated in the reserve base category. The compilation of company reported economic PGM reserves in 2007 (Table 4) of 68,661 t PGMs correlates well with the USGS figure of 71,000 t PGMs as reserves (some projects and companies are not included in Table 4). Although Gordon et al. (2006) suggested that Pt could be in short supply within a few decades as demand continues to grow, this proposition is not supported by the available reserves data or projections using a 'peak' model. Furthermore, tentative concerns were raised in the late 1960's about the future availability of Pt, with reasonably confident assessments pointing to extractable resources of at least 6220 t Pt from 1970 to 2000 (Hunt and Lever, 1969) – over this same period South African production was 2245 t Pt (noting present resources in Table 4). The extent of recoverable resources was linked to ore grades and mining depth, with considerable potential for continuing to increase reserves for some time (Hunt and Lever, 1969). A review of recent company annual reports shows that almost all major PGM companies in South Africa have maintained and/or increased their PGM reserves, at least over the past decade. Further to this, as noted by Cawthorn (1999, 2007), most reserves in the Bushveld Complex are only estimated to a mining depth of 2 km (current economic mining limit), with considerable potential for additional PGMs known at greater depths as well as in other lower grade reefs (1–3 g/t) not currently exploited – potential PGMs could reach 311,000 t in the Bushveld alone (Cawthorn, 2007). Thus the critical sustainability issue in the future is not resource size but the associated environmental costs.

The environmental data compiled and analysed in this study is mainly from the past 5 years, with production data just over a decade. Thus it is not possible to establish long term trends (>10 years) in these aspects. However, the basic approach to PGMs mining and production has not changed significantly since the 1930s, although improvements in concentrating, smelting and refining methods have been developed to allow economic production from the UG2 reef and Platreef. For comparison, in 1955 the Rustenburg and Union mines processed about 1.6 Mt of ore, consumed 306,000 GJ of electricity and 2,157,000 m^3 of water (RPM, 1957). Assuming all South African production of 11.87 t PGM in 1955 was from these mines, this gives a yield of about 7.42 g/t (an ore grade of 9.3 g/t assuming 80% recovery) as well as a unit energy and water cost of 25.8 GJ/kg PGM and 182 m^3/kg PGM, respectively, plus 1.35 m^3/t ore. These values compare to recent values of 100–255 GJ/kg PGM, 214–1612 m^3/kg PGM and 0.68–2.33 m^3/t ore, respectively (Table 5), suggesting that energy costs have increased over time (even allowing for some additional direct energy in 1955) but water costs have only marginally increased. The increasing energy costs are probably related to the gradually increasing depth of the mines.

With respect to energy, the data shows a moderate negative correlation between ore grade and unit energy costs. That is, as ore grades decline the unit energy costs increase (Fig. 6). Although average PGM ore grades in the Bushveld have not declined as dramatically as Au ores (see Mudd, 2007), the current average ore grade of about 4.45 g/t (Table 2, Bushveld only) is very close to the average ore grade of economic reserves of 4.28 g/t (Table 4). Average ore grade may decline as some shallower but lower grade projects (e.g. Potgietersrust, Great Dyke mines) are expanded or developed in preference to deeper Merensky-UG2 projects. Overall, this suggests that total energy consumption will largely be a function of PGM production, with only slight pressure on energy costs from declining grades. Declining grades, however, may still be relevant for individual companies or major projects (i.e. Fig. 4).

Unlike Au mining, PGM mining and production is dominated by electricity consumption, related to the primacy of underground mining in the Bushveld region and more complex processing required compared to Au production. The typical range for unit energy costs is presently 100–255 GJ/kg PGM, with a production-weighted average of 175 GJ/kg PGM. Most projects show variable unit energy costs over time and no clear trend, although 2007 or 2008 is often the highest on record and is presumably related to the South African electricity supply crisis which is limiting production. In a recent and similar study of Au mining, Mudd (2007) showed that the typical unit energy costs of Au range from 120 to 213 GJ/kg Au and averaged 143 GJ/kg Au. The unit energy costs for PGMs are clearly higher than Au, but not as much as could be expected based on the differences in mining and processing.

Due to detailed sustainability reporting by Anglo Platinum, the split in energy costs between mining, milling, smelting and refining was included in Table 5, showing the dominance of the first three of the four major stages in PGMs production. In addition, the inclusion from 2006 to 2007 of energy costs split between mining and milling is a rare such example in the global mining industry, and allows improved understanding of the various stages of PGM mining and production. Unfortunately, as individual smelter PGM production statistics are not reported (e.g. grade and tonnes of concentrate processed to matte produced), this prevents a breakdown to unit energy costs (GJ/kg PGM) for each major stage which could then be expanded into a rigorous, process-based model of PGMs. It is hoped that future sustainability (and financial) reporting continues to expand in scope and rigour, allowing more comprehensive analyses in the future.

The unit GGEs also show a moderate correlation to ore grade, similarly to energy – as should be expected given the dominance of coal in South Africa's electricity mix. The typical range for unit emissions is 24.8–78.3 t CO_{2-e}/kg PGM, with a production-weighted average of 39.4 t CO_{2-e}/kg PGM. The unit GGEs for Au typically range from 10.3 to 16.4 t CO_{2-e}/kg Au and averages 11.5 t CO_{2-e}/kg Au (Mudd, 2007). The significantly higher unit GGEs for PGM production is influenced by the high proportion of electricity for Bushveld projects and the dominance of coal in South Africa's electricity mix.

The energy and GGEs intensity of Bushveld PGM production gives rise to perhaps a unique situation in global mining. Due to the high proportion of electricity, it should be possible to examine future low GGE electricity sources, such as renewable energy projects like solar thermal and/or photovoltaics, to progressively replace existing coal-based electricity. This would still allow electricity needs to be met but provide for a significant reduction in emissions. In contrast, energy consumption in Au mining is often dominated by open cut mining, for which sustainable alternatives to diesel appear very limited (at present). Although viable energy sources in the Bushveld are outside the scope of this study, it is clear that energy efficiency as well as energy sources will be critical in determining the energy and emissions intensity of PGM production.

The extent of water consumption for PGMs is within typical ranges for various metals (see Mudd, 2008). In terms of water consumed in milling, the range in this study for processing PGM ore is 0.56–2.33 m^3/t ore with one project averaging some 12.6 m^3/t ore. The average of 1.32 m^3/t ore (excluding the high value) is similar to Au (1.37), Cu–Au (1.22), Cu (1.27), lead–zinc–silver (2.67) and nickel (1.01) ore processing (all m^3/t ore and a variety of project scales and configurations; see Mudd, 2008). Almost all of these ore types undergo grinding and flotation to produce concentrates in a similar manner to PGM ore processing.

A perhaps surprising outcome is the degree to which the Lebowa mine and mill has reduced water consumption from a high of 6.07 million m^3 in 2004 to just 279,000 m^3 in 2008. Unfortunately, the reasons for this are not explored in Anglo's sustainability reporting. Most projects, however, have not been successful in this regard, with Anglo's Rustenburg project increasing total consumption water from 8–9 million m^3 over 2002–2004 to about 11 million m^3 in 2008 despite similar production levels. The opportunity to save water would appear to be very site and project specific but remains a critical area for future sustainability in the PGM sector.

Despite the increasing reporting of water consumption by PGM companies, it remains a challenging area for sustainability reporting. Under the GRI, total water consumption (EN8) and water discharges (EN21) are core reporting indicators while impacts on water resources (EN9) and water recycling (EN10) are voluntary. Very few PGM companies report on all of these indicators in detail, with most simply reporting total water consumption. As such, it has not been possible to present an account of the extent of recycling in PGM ore processing.

The typical range for unit water consumption per PGMs produced of 214–1612 m^3/kg PGM, with a production-weighted average of 391.5 m^3/kg PGM, compares similarly to Au mining where production requires an average of 691 m^3/kg Au (typical range 224–1783 m^3/kg Au) (Mudd, 2007). The higher average unit water cost for Au over PGMs is probably related to the lower average grade of Au mines (~2 g/t) – despite the more intensive smelting and refining for PGMs. Since production statistics for smelting and refining are not reported by PGM companies, allocating water per PGM production across the four principal stages is not possible. Based on total water consumption reported by Anglo Platinum, the total water required by the mining-milling, smelter and refining stages for 1–2 Mt ore/year are broadly similar at about 1–2 million m^3/year, with throughputs of 4–12 Mt ore/year having larger water requirements up to 4–10 million m^3/year for the mining-milling stages.

A major weakness in the GRI's approach to water aspects is that water quality is not considered, except for external water discharges to the environment (see Mudd, 2008). This is critical since water quality is the primary factor in determining its potential use, recyclability and its potential impact on the environment. At present, all PGM companies do not divulge data on the quality of water reported as consumed in projects, with limited information or statements on the quality of water discharged to the environment (noting the Anglo Platinum statement on water resource impacts at Potgietersrust versus those of ActionAid discussed earlier).

The mining industry is the largest annual producer of solid wastes globally (see IIED and WBCSD, 2002; Da Rosa et al., 1997). With PGM ores grading g/t, this means that >99.99% of the ore becomes solid waste. However, despite numerous major tailings dam failures, riverine or marine disposal of tailings, or ongoing acid and metalliferous drainage at innumerable current and former mine sites around the world (IIED and WBCSD, 2002; Da Rosa et al., 1997; Taylor and Pape, 2007; Blowes et al., 2007), the GRI still does not mandate that large volume mine wastes be fully and accurately reported. Under the main GRI protocol (GRI, 2006), the core indicator for solid wastes (EN22) is typically taken to refer to putrescible and/or hazardous wastes, such as those sent to landfill, recycled or treated further (e.g. chemicals, oils, metals, woods, etc.) (Mudd, 2009a). The GRI mining sector supplement still only expects 'hazardous' mine wastes to be reported, effectively leaving the reporting of large volume mine wastes at the discretion of a site 'risk assessment' (Mudd, 2009a). This is unfortunate, since it allows an easy escape clause for companies to justify not reporting such wastes. Based on a comprehensive survey of sustainability reporting by many major global mining companies, full and accurate reporting of large volume mine wastes is a key strategic weakness across numerous companies (Mudd, 2009a). Anglo Platinum are certainly the leader with respect to reporting mine waste data, although all PGM companies can and need to improve their sustainability reporting in this regard.

A relatively recent advance in understanding the environmental impacts of PGM projects is that the mining and processing of PGM ore can lead to the formation of trace amounts of dioxins, furans and polychlorinated biphenyls (Jordaan et al., 2007). This is due to the presence of chlorine, carbon and oxygen in the presence of catalysts during high temperature smelting processes. At present, it appears that dioxins are the dominant source of toxic equivalence, and although the overall risk appears to be relatively low, further research is needed (especially in understanding dioxin formation in varying smelter operating conditions).

A final issue, of potentially growing significance in the medium term future, is the emergence of elevated Pt concentrations in urban areas arising from catalytic converters (Hutchinson and Pearson, 2005; Sures et al., 2002; Ravindra et al., 2004). As with urban traffic-derived lead, research shows that Pt concentrations in dusts and soils are closely correlated to distance from roads, with city centres showing higher Pt concentrations than residential areas. Furthermore, recent research has shown that mussels are capable of bioaccumulating Pt, Pd and Rh (Sures et al., 2002; Ravindra et al., 2004). At present there is little known about the long term health and environmental effects of such low Pt exposure, with the main knowledge concerning acute exposure scenarios to Pt salts (Hutchinson and Pearson, 2005; Ravindra et al., 2004). It is clear that removing lead from active use in transport fuels has led to net public health benefits (Hutchinson and Pearson, 2005), and although there is no evidence that the increasing Pt levels are leading to significant effects, this issue should be treated with caution and requires ongoing monitoring and research.

6. Conclusion

In summary, this paper has studied the PGM mining sector, compiling and analysing an extensive array of data on production, resources, energy and water costs and greenhouse gas emissions. In terms of production and resources, there is strong evidence to suggest that there are indeed extensive PGM resources available, concentrated principally in the Bushveld Complex of South Africa and additional resources in Zimbabwe, Russia, the United States and Canada. The main question is therefore not the extent of known resources but rather the environmental costs of PGM production. Despite being similar in grade to Au ores, PGM ores are processed in a manner more akin to base metal ores – yet the data compiled in this report shows that unit environmental costs for PGMs are only slightly higher in energy, slightly lower in water and moderately higher in greenhouse gas emissions than gold mining. The evidence for improving efficiencies over time is weak, although only a few years are available for many projects. The PGM ore grade does appear to be a reasonably important factor in understanding issues such as unit energy costs and greenhouse gas emissions in PGM production, though ore grades are not likely to decline significantly since current projects are similar to known ore resources. Given the dominance of electricity in energy consumption, there are perhaps unique opportunities available for PGM mining to investigate the use of renewable energy technologies, and thereby reduce greenhouse gas emissions. Water consumption is a critical issue, especially in an arid region such as north-west South Africa, with variable evidence for select PGM projects showing either major decreases or increases in water consumption. The extent of impacts on water resources remains contested and uncertain. Overall, the environmental costs of PGM production are significant but appear to be related mainly to production levels – and given the likely future demand, the cumulative environmental costs in such a concentrated region provide both a major challenge and opportunity with respect to sustainability. For PGMs, whether the environmental glass is half-full or half-empty is essentially in the eye of the beholder.

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