The Environmental Costs of Platinum-PGM Mining: An Excellent Case Study In Sustainable Mining

*Gavin M. Mudd[1], Bonnie J. Glaister[1]

[1]Environmental Engineering, Department of Civil Engineering,
Monash University, CLAYTON, Victoria, Australia 3800
(Corresponding author: *Gavin.Mudd@eng.monash.edu.au)

ABSTRACT

The platinum group of 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 (eg. catalytic converters, fuel cells, electronics). The typical ore grade for PGM mineralisation is similar to gold (g/t) but the processing is more akin to base metals (at percent). The typical scheme for a PGM project is a mine, flotation concentrator, smelter and refinery. The environmental costs could therefore expected to be more significant than gold mining – in contrast to the uses for PGMs in many environmentally focussed technologies. The global production of PGMs is dominated by South Africa due to their large economic PGM resources in the Bushveld Complex, while other countries play a minor but important role. Concerns are being raised about the long-term ability to supply PGMs to meet future technological needs, as well as allegations of significant environmental and social impacts such as water pollution, unfair village relocation and compensation issues. This paper presents a detailed review of the platinum-PGM industry and major environmental costs such as water, energy and greenhouse emissions. The relationships between production statistics and environmental or 'sustainability metrics' are then investigated with a view to understanding the current trends in PGM mining and potential future implications. 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.

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INTRODUCTION

The platinum group of metals (PGMs) have shown one of the highest long term growth rates of numerous mineral commodities over the past 50 years, due to their unique physical and chemical properties which make them ideal for a wide variety of technologies. Applications for PGMs include catalysts for chemical process facilities (eg. oil refineries), catalytic converters for vehicle exhaust control, hydrogen fuel cells, electronic components, jewellery, and a variety of specialty medical uses. Given the need to expand many of these uses to meet environmental challenges such as resource efficiency and pollution control, PGMs demand can reasonably be expected to be sustained for a significant period of time.

The typical ore grade for PGM mineralisation is similar to gold, at grams per tonne (g/t), but the processing is more akin to base metals (at percent). The typical scheme for a PGM project is a mine, grinding, gravity-based separation, flotation concentrator, smelter and refinery. The environmental costs could therefore be expected to be more significant than gold mining – in contrast to the uses for PGMs in many environmentally focussed technologies. Some PGMs are also extracted as a by-product (or co-product) from the processing and smelting of base metal ores (eg. Ni, Cu ores).

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 useful role. Although known economic resources continue to reflect current production growth, concerns are being raised about the long-term ability to supply PGMs to meet future technological needs (eg. [1-2]), as well as allegations of significant environmental and social impacts such as water pollution, unfair village relocation and compensation issues (amongst others) [3].

This paper presents a detailed review of the PGM industry and major environmental costs such as water, energy and greenhouse gas emissions, and focussing on South Africa. A range of data is compiled, including annual production, major inputs ands 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. 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.

PLATINUM-PGM MINING AND PROCESSING

Overview

The six platinum group metals have similar physical and chemical properties, 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) [4]. Due to their high corrosion and oxidation resistance and relative scarcity in the earth’s crust, along with gold (Au) and silver (Ag), PGMs are classified as noble and precious metals. Common abbreviations used are ‘4E’ (or 3E+Au) which includes Pt, Pd, Rh and Au, while 6E (or 5E+Au) includes Pt, Pd, Rh, Ru, Ir and Au.

In 2007, global PGM production was about 509 tonnes, consisting of 165.8 / 86.5 t Pt/Pd from South Africa, 27 / 96.8 t Pt/Pd from Russia, 6.2 / 10.5 t Pt/Pd from Canada, 5.3 / 4.2 t Pt/Pd from Zimbabwe and 3.9 t Pt and 12.8 t Pd from the United States [5]. Historical production and price is shown in Figure 1. The PGMs are one of the very few metals which have stayed relatively constant in their real price over time [6]. According to the USGS [7], global economic reserves are about 71,000 t PGMs, with an additional 81,000 t PGMs in the reserve base category – about 88% is in South Africa, with 8% in Russia.

Platinum-PGM Mining and Processing

There are broadly considered to be four main types of economic PGM mineral deposits [4]:

- **Norite intrusions** – where meteoritic impact has been instrumental in PGM emplacement; eg. Sudbury Irruptive Complex in Ontario, Canada (~10-1000 Mt, 1-3 g/t, ~2-3% Ni+Cu).

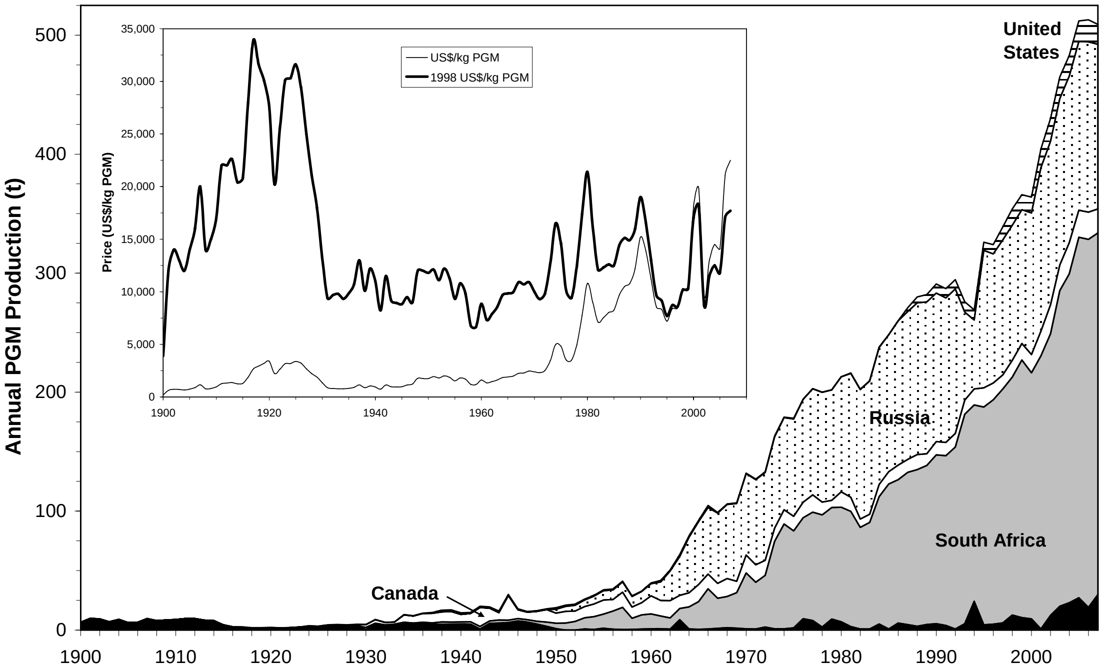

Figure 1 – Historical platinum-PGM production and price (inset) (data combined from [4-7])

- **Stratiform deposits** – where PGMs occur in large Pre-Cambrian mafic to ultramafic layered intrusions, such as the Merensky and Upper Group 2 Chromitite (UG2) Reefs of the Bushveld Complex in South Africa, Great Dyke in Zimbabwe and the Stillwater complex in Montana, United States (usually ~10-1000 Mt, grade 3-10 g/t PGMs, ~0.2-1% Ni+Cu).
- **Ni-Cu bearing sills** – related to rift structures and concordant intrusive sheets, eg. Noril'sk-Talnakh District, Russia, and Jinchuan deposits, China (~10-1000 Mt, 5-10 g/t, ~3-5% Ni+Cu).
- **Placer deposits** – alluvial deposits containing coarse PGMs (mainly Pt) were mined with alluvial gold for ~2,000 years prior to the 20th century . Columbia produced 1.4 t alluvial Pt in 2007 [5].

The mining of PGM ores is through conventional underground or open cut mines. 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 [4]. The concentrate is then smelted to produce a PGM-rich Ni-Cu matte, with the PGMs extracted and purified at a precious metals refinery. The processing is therefore more analogous to base metals rather than Au-Ag mills which use cyanide-based hydrometallurgy. Smelting of Ni-Cu concentrates can also be a modest source of PGMs (eg. Russia, Canada). Further details are given by Vermaak [4] and Cabri [8].

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 up to 240 km north-south [4]. 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. Outcrop of the Bushveld complex occurs in three principal areas, with two bracket-like lobes on the west and east side plus a linear northern lobe. A regional and local map is given in Figure 2. Further geological details are given by Vermaak [4] and Cawthorn et al [9], amongst others.

The presence of Pt in the Johannesburg gold fields region was well established by the end of the 19th century, mainly as a scientific curiosity. In 1906 Pt was discovered 'in situ' sparking two decades of unsuccessful exploration and research.

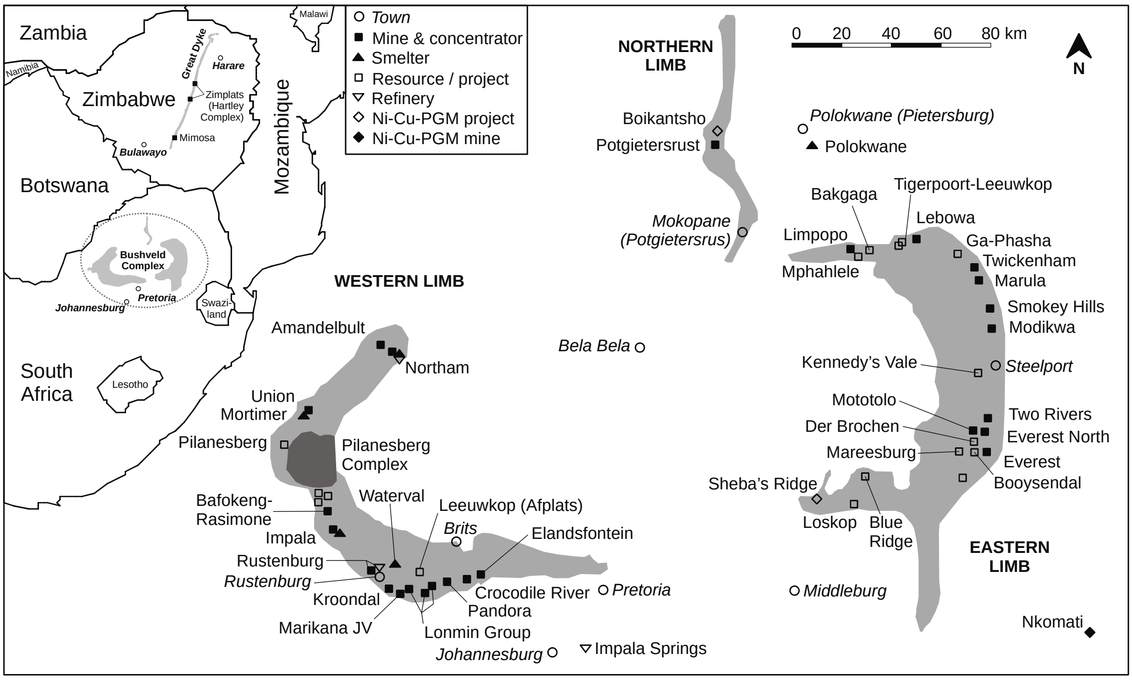

Figure 2 – Location map of South-eastern Africa and the Bushveld Complex– PGM mines, smelters, refineries and future projects

In 1924, geologist Hans Merensky followed up on a sample sent to him from a Bushveld farmer, and confirmed it was Pt but of a coarse nature and therefore potentially economic. The source is now called the Merensky Reef, and is found throughout the Bushveld Complex. The original chromitite mineralisation noted in 1906 is called the Upper Group 2 Chromitite (or UG2) Reef.

The northern limb of the Bushveld Complex contains the Platreef – the centre of PGM mining during the late 1920s, although mining failed to prove profitable and ceased. Anglo Platinum developed the first commercial Platreef mine at Potgietersrust in 1993. The Platreef is a focus for exploration, however Platreef mineralisation and its relationship to the Bushveld Complex are still poorly understood.

Both the Merensky and UG2 reefs are remarkably continuous over tens to hundreds of kilometres, with the PGMs mineralogically associated with base metal sulfides [4]. Due to the very thin nature of the Merensky and UG2 reefs (~1 m), mining typically requires narrow techniques (eg. vein-style) rather than bulk, high tonnage methods. Although earlier mines were based largely on the Merensky Reef, the UG2 Reef is now increasingly being mined. The Platreef is slightly thicker (~4 m) and is mined by open cut at Potgietersrust due to the shallower depth of the reef. The depth of individual underground mines can range from 100 to ~2000 m, with most presently active around several hundred metres.

A statistical summary of most PGM producers is given in Table 2, major Ni-Cu-PGM mines are summarised in Table 3, and economic resources reported by company and ore type is shown in Table 4. All contained data is compiled from respective company annual reports.

Platinum-PGM Demand and Uses

The uses for platinum and 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. The demand by use since 1975 is shown in Figure 3.

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

Company	Project & Mine Type	Mt ore/yr	4E g/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
AquaPt t $^{100\%}$	Everest (UG $^{70.2\%}$)	1.988	2.96	2.539	1.355	0.411	0.039	5.212
AquaPt $^{50\%}$-AngloPt $^{50\%}$	Kroondal JV (UG $^{93.7\%}$)	4.843	3.62	6.042	2.887	1.056	0.049	15.158
AquaPt $^{50\%}$-AngloPt $^{50\%}$	Marikana JV (OC $^{77.8\%}$)	1.490	4.30	1.836	0.787	0.249	0.023	4.149
AfrRainMin $^{41.5\%}$-AngloPt $^{50\%}$	Modikwa JV (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					
Lonmin $^{100\%}$	Limpopo (UG)	0.608	3.74	25.10	11.31	3.299	0.612	44.109
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 $^{73\%}$	Marula (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)	4.732	2.16 ^{Pd}	0.660	7.327	-	0.582	-
	Totals	**90.13**	**4.52**	**163.5**	**102.8**	**19.47**	**5.04**	**290.8**

Notes: AngloPt – Anglo Platinum; AquaPt – Aquarius Platinum; AfrRainMin – African Rainbow Minerals; $^{xyz\%}$ denotes %ownership.

Table 3 – Recent average production for major Ni-Cu-PGM projects

Company, Project	Mine Type	Mt ore/yr	%Ni	%Cu	PGM g/t	Ni kt/yr	Cu kt/yr	Pt t/yr	Pd t/yr
Norilsk Nickel, Taimyr, Russia	UG/OC	14.52	1.65	2.87	9.30	123.7	350.9	23.13	96.89
Vale Inco, Sudbury, Canada	UG/OC	7.81	1.36	1.46	~2.5	90.7	111.4	4.87	6.02
AfrRainMin, Nkomati, S Africa	OC	0.49	1.36	~0.8	~3	5.3	3.0	1.4 t PGMs	

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

Reef / Ore Type	Mt ore	4E g/t	t PGM (4E)
Merensky	2,952	5.01	14,796
UG2	5,329	5.05	26,922
Platreef	3,063	2.29	7,023
Great Dyke	2,069	3.65	7,560
Tailings	238	0.90	214
Subdury (Canada) – Ni-Cu-PGMs	160.3	2.0	321
Taimyr (Russia) – Ni-Cu-PGMs	2,216	5.04	11,169
Stillwater (USA) – PGMs	40.0	16.4	656
TOTAL	**16,068**	**4.27**	**68,661**

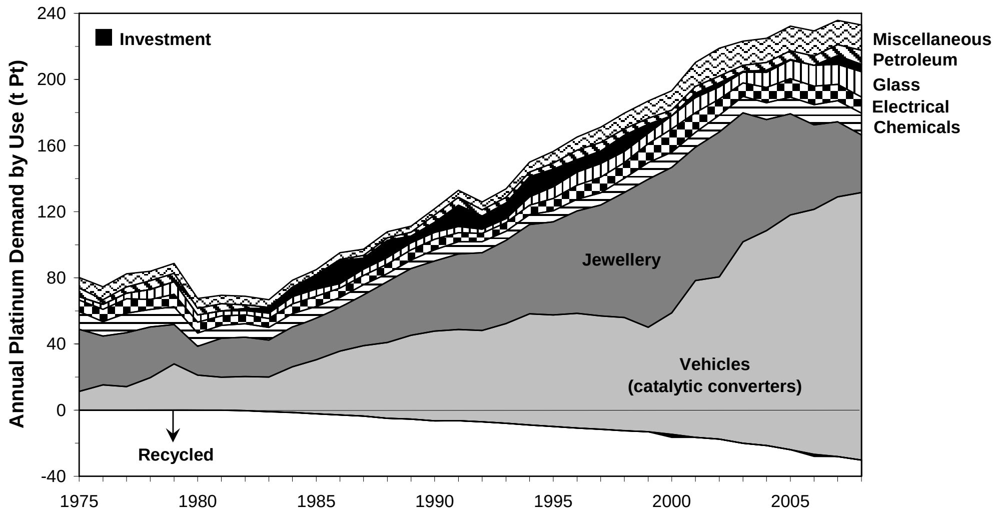

Figure 3: Demand for platinum by use, 1975-2008 [10]

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.

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 [11], including many South African and especially PGM companies. In general, sustainability reports cover the environmental, economic and social performance of a company alongside financial reporting. The compilation and analysis of the reported data can provide critical insights into a given sector of the mining industry, 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.

Sustainability and Mining

At first glance, applying the principles of sustainability to mining is seemingly a simple oxymoron – since mining means to extract a mineral or metallic resource which is, in reality, 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 [11].

It is easy to take known economic resources and divide by annual production, and assume that this means ‘x’ years remaining. On one side this under-estimates longevity due to the potential to find new resources, new technology(eg. gold [11]), recycling and resource efficiency. Alternately, longevity could be over-estimated as demand continues to grow. In reality, the classification of a resource as ‘economic’ is variable over time. For example, new discoveries can change production costs, or changes in market prices can affect economic status. While there is evidence to suggest that many minerals have shown growth in economic resources, as demand/supply links to exploration, technology and price – it is increasingly clear that the historical patterns of mineral supply cannot be assumed to continue unaltered into the future. The constraints may vary from social issues to water or energy/greenhouse resources.

With respect to mining, the application of sustainability principles is therefore complex. The global mining industry released a major report on mining and sustainability for the Johannesburg Earth Summit in 2002. The ‘Mining, Minerals and Sustainable Development’ report [12] was a major shift from arguing the historical case of growing resources over time (as above), to a position where mining can contribute to sustainable development (even if a mine itself 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 (ie. the Brundtland definition). In the context of mining, this can be taken to include the availability of resources and a productive environment at former mine sites. The context for sustainable development and mining can therefore be simplified as balancing the potential environmental, social and economic risks. In the context of the grand challenges of the millennia, such as climate change, development and equity (amongst many others), this is not a mere formula – but a fundamental challenge for all concerned.

Sustainability Reporting

An increasingly popular way of demonstrating sustainability performance is through sustainability reporting, focussing on social, economic and environmental aspects. Early methods for environmental or sustainability 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 enhance sustainability reporting. The third edition was released in 2006 [13] and a draft mining sector supplement was released in early 2009 [14]. The GRI itself is voluntary, and can be applied in whole or in part, with five main sections including economic, environmental, labour practices, human rights and social aspects. Qualitative or quantitative indicators used for each area, stated as core or voluntary for reporting. The degree to which the GRI is followed can then be assessed and given an ‘application level’ to guide the level of assurance the report could be considered to provide.

The principal core environmental indicators of relevance are: EN3 / EN4 – direct / indirect energy sources; EN8 – total water used by source; EN16 – total direct and indirect greenhouse gas emissions; EN21 – total water discharge by quality and destination; EN22 – total weight of waste by type and disposal method. Voluntary environmental indicators of relevance are: EN9 – water sources significantly affected by water withdrawal; EN10 – percentage and total volume of water recycled and reused. Based on the draft mining sector supplement [14], large volume mine wastes, such as tailings and waste rock, only need to be discussed with respect to site-specific risk assessment – it is not core to report such wastes (see later).

Overall, the emergence and continuing improvement in sustainability reporting is providing a valuable source of data to assess the environmental sustainability aspects of mining. Platinum-PGM companies in South Africa are certainly at the forefront in this regard.

Quantifying Sustainability and PGMs Production

The available data on wastes, energy, water and greenhouse gas emissions from sustainability reporting can be combined with production. In this way it is possible to link aspects such as energy, water and greenhouse 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. The ‘resource intensity’ metrics we use are unit consumption/ emissions per PGM production (eg. GJ/kg PGM, m^3/kg PGM, t CO_{2-e}/kg PGM) with respect to ore grade (4E g/t), as well as unit consumption/emissions per tonne milled (e.g. m^3/t ore, GJ/t ore, t CO_{2-e}/t ore) with respect to mill throughput (Mt ore/year). Analysis of some company-wide performance is also presented.

RESULTS

PGMs Production

In general, the reporting of production statistics is reasonably consistent, such as ore grade as 4E g/t, individual PGM production (Pt, Pd, Rh, Au, sometimes Ru and Ir) and economic resources. Based on current economic resources and production (Tables 2, 4), ore grades are relatively stable and will remain ~3-5 g/t (however, some companies may show slight declines). In the early 1990’s the proportion of UG2 ore was of the order of 30% [4], while the mix is now ~65/~26/~9% UG2/Merensky/Platreef, respectively. Recent production data (Table 2) shows that underground mining represents 88.6% of PGM ore milled, with 11.4% by open cut mining (some small underground mines are missing in Table 2; eg. Elandsfontein).

Water and Energy Consumption

The reported unit water and energy consumption metrics versus ore grade or throughput are shown in Figure 5. Data is separated into mine plus concentrator projects versus mine, concentrator and smelter projects, with all results summarised in Table 6.

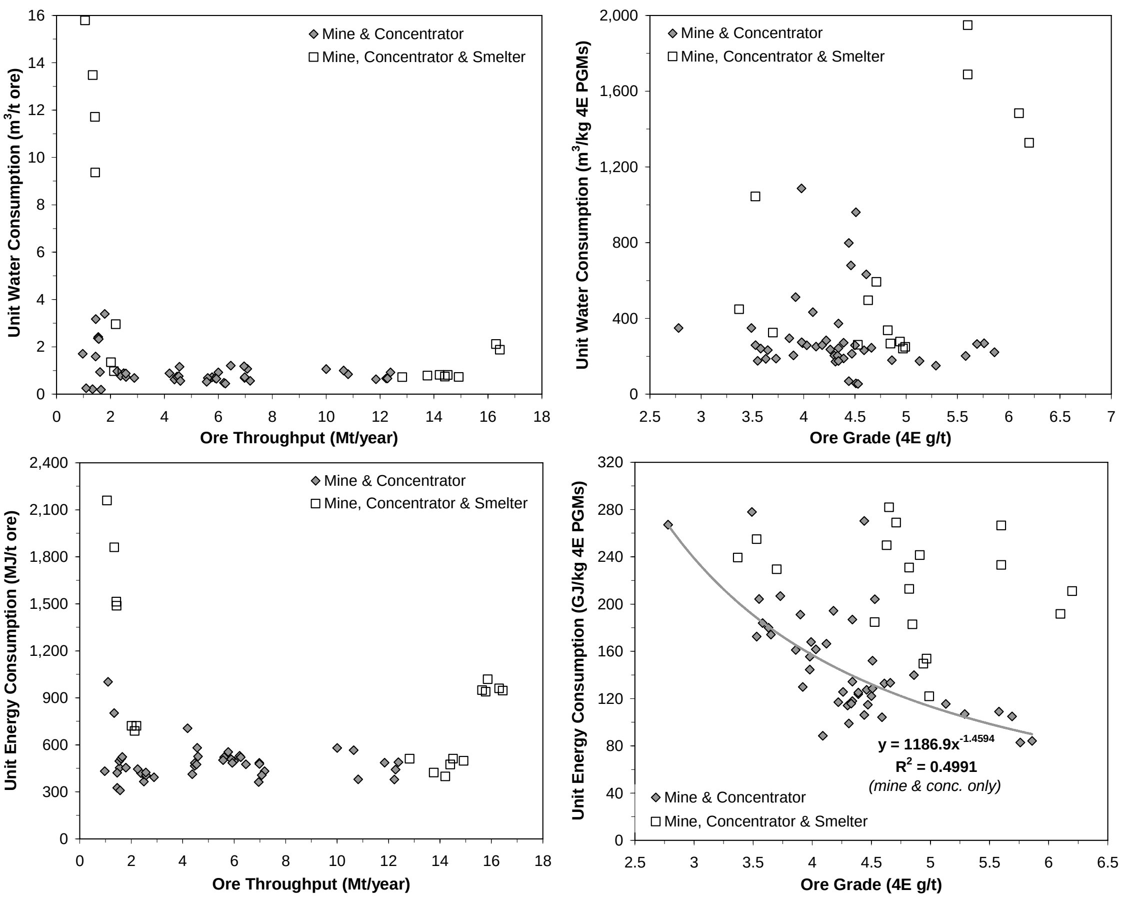

Figure 5: Unit consumption metrics – water versus ore throughput (top left), water versus ore grade (top right), energy versus ore throughput (bottom left), energy versus ore grade (bottom right)

Table 6 – Summary of environmental sustainability metrics by PGM mine/project or group (number of data points in brackets)

	Mining	**Milling**	**Total**	**Total**	**Water**	**Water**	**Emissions**
Mine / Project	**MJ/t rock**	**MJ/t ore**	**GJ/ kg PGM**	**MJ/t ore**	**m^3/ kg PGM**	**m^3/t ore**	**t $CO_{2\text{-}e}$/ kg PGM**
Bafokeng-Ras.[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)	-
Marula[MC]	-	-	108 (3)	393 (3)	582(3)	2.155 (3)	-
Croc. River[MC]	-	-	145 (1)	310 (1)	1,086 (1)	2.328 (1)	33.6 (1)
Northam[MCS,§]	1,268 (4)	487 (4)	226 (4)	1,755 (4)	1,612 (4)	12.6 (4)	78.3 (1)
Zimplats[MCS]	-	-	241 (3)	710 (3)	606 (3)	1.760 (3)	-
Company	**Energy Fraction Direct**	**Energy Fraction 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)	255 (5)	962 (5)	544 (2)	1.998 (2)	50.0 (5)
Lonmin[MCS]	20.1% (4)	79.9% (4)	168 (6)	469 (6)	272 (6)	0.768 (6)	39.5 (6)
Northam[MCS,§]	7.9% (4)	92.1% (4)	226 (4)	1,755 (4)	1,612 (4)	12.59 (4)	78.3 (1)
Anglo Plat.[MCS]	23.6% (4)	76.4% (4)	-	-	-	-	-
Energy Fraction	**Mining**	**Milling**	**Smelting**	**Refining**	**Other**		
Anglo Plat.[MCSR]	41.0%	23.5%	25.7%	3.5%	6.3%		

Note: MC – mine and concentrator; MCS – mine, concentrator and smelter; number of years of data in brackets.
[§]Assuming coal is used in milling/smelting only and diesel is used in mining only.

Figure 5 shows no substantive evidence for improved water or energy unit efficiency at higher throughputs. There does appear to be higher unit energy consumption for stand alone projects with low throughputs. Ore grade does not appear to be a factor in unit water efficiency but does appear to be significant for unit energy consumption (Figure 5). The low energy cost at Potgietersrust (21 MJ/t rock) is due to this being an open cut mine, while the deep (~2km) and small Northam underground mine has the highest mining unit energy consumption (1,268 MJ/t rock). The results also show that electricity is the dominant (indirect) energy input overall, with underground mining being the major user (related to the narrow reef mining techniques used). 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 to open cut mines shows that there is a trade off between the energy used in underground versus open cut mining (ie. MJ/t rock) and the solid wastes produced, since open cut mining produces large volumes of waste rock (see later section).

Greenhouse Gas Emissions

The reported greenhouse gas emission (GHG) metrics versus ore grade and unit energy costs versus unit greenhouse gas emissions are shown in Figure 7. A weak relationship is suggested between ore grade and unit emissions (correlation coefficient 38.1%), while the correlation between unit energy and unit emissions, surprisingly, only yields a correlation coefficient of 63.4% (Figure 7) – despite South Africa's electricity supply being dominated by coal (89.7%) with a small proportion of hydro-electricity (5.0%). The variability could be due to different estimation methods used by companies, although given the dominance of electricity this would not expected to be the case. The values which appear to be outliers are Northam – one of the deepest mines (~2 km) and is a smaller scale, stand alone project.

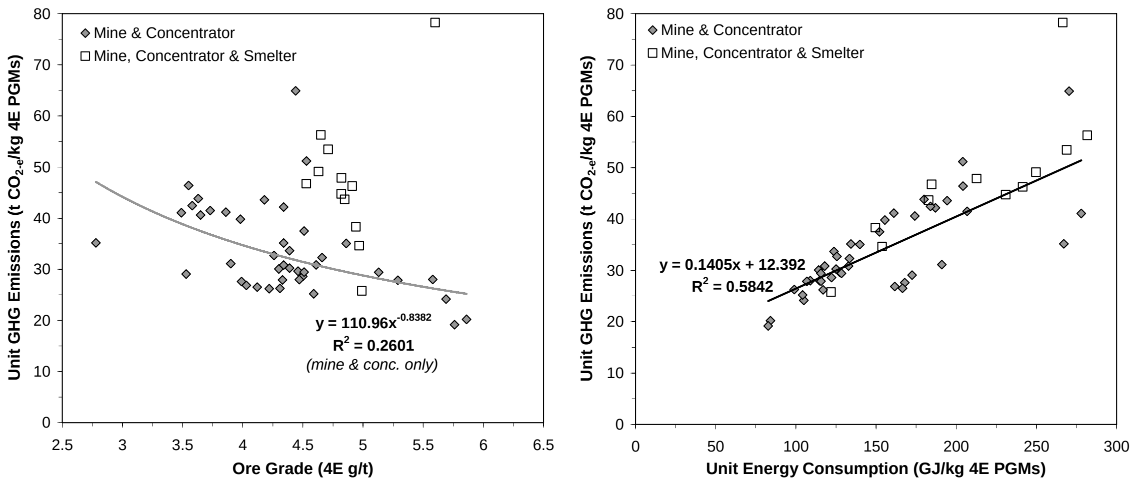

Figure 7: Unit greenhouse gas (GHG) emissions versus ore grade (left) and unit energy costs versus unit greenhouse gas emissions (right)

There is some evidence for PGM producers showing declining ore grades over the past decade (data not shown), the implication being that unit GHG emissions could begin to increase if no action is taken (eg. improving energy efficiency or increasing renewable energy sources). Some companies are also now responsible for GHG emissions of the order of several millions of tonnes – and if production continues to grow similar to historical rates, this will lead to major increases in total GHG emissions.

Based on the data in Figure 7 and Table 6, the GHG emissions growth due to production increases is likely to be much greater than possible savings due to mine/mill/smelter efficiency improvements. Although data over time is not presented, energy savings achieved at most sites are relatively modest or cancelled out by other factors such as operational issues (eg. South African electricity crisis). For example, some Anglo Platinum mines show variation within a typical range (eg. Bafokeng, Union), while others show a gradual increase over time (eg. Lebowa, Potgietersrust, Amandelbult, Rustenburg). In other words, if production doubles there is little evidence that existing mines can reduce energy consumption by half.

Solid Wastes – Waste Rock and Tailings

There are two large volume wastes in mining – tailings and waste rock. Both types of wastes require active assessment, planning and management to prevent major environmental, social or financial impacts such as tailings dam failures (eg. 1974 Bafokeng tailings disaster), acid mine drainage or other problems (eg. dust, environmental health issues). In addition, slag wastes from smelters are important and are commonly disposed of in tailings dams. Given that the ratio of ore to concentrate is typically around 30 to 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 (eg. 5 to 20:1) and the reverse for underground mining. At present, there is no data available on underground waste rock generation, and given the narrow nature of the reefs, waste rock:ore ratios could be expected to be higher than bulk, high tonnage methods.

In the Bushveld, waste rock:ore ratios range from about 7 to 20, giving annual waste rock at open cut mines of some 125 Mt (dominated by Potgietersrust). Studies by Anglo Platinum 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 sulphate (see their 2007 sustainability report) – meaning tailings still require active environmental management to prevent impacts on water resources. The ActionAid report [3] argued that there were impacts on water resources, especially Potgietersrust, and this was addressed by Anglo Platinum (2008 sustainability report), who commissioned studies to suggest that the signatures of the mine and local waters were different. This issue highlights the importance of managing large tonnage mine wastes, especially adjacent to large indigenous populations dependent on adjacent water resources.

DISCUSSION

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

A common concern raised about mining is that resources are finite and could therefore soon 'run out'. For PGMs, however, there is compelling evidence that resources will not be limited in the near future. At 2007 production of 509 t and reserves of 71,000 t PGMs, sufficient PGMs are within normal economic criteria for existing fields such as the Bushveld, as well as the strong prospects for reserves to continue to grow, based on the deep geology of the Bushveld. Thus the critical sustainability issue in the future is not the total available resource but the environmental costs and impacts.

The environmental data compiled and analysed in this study is mainly from the past 5 years, with production data just over a decade. For comparison, in 1955 the Rustenburg and Union mines processed ~1.6 Mt of ore and consumed 306,000 GJ of electricity and 2,157,000 m^3 of water [15]. Assuming all South African production in 1955 (11.87 t PGM) was from these mines, this gives 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 milled. These values compare to recent values of 100 to 255 GJ/kg PGM, 214 to 1,612 m^3/kg PGM and 0.68 to 2.33 m^3/t milled, respectively (Table 6), suggesting that energy costs have increased over time but water costs have only marginally increased. The higher energy costs are probably related to the increasing depth of the mines. The typical range for unit energy costs is presently 100 to 255 GJ/kg PGM, with an average of 175 GJ/kg PGM. Most projects show variable unit energy costs over time and no clear trend, with 2007 or 2008 often the highest on record and is presumably related to the South African electricity supply crisis. In a recent study of gold, Mudd [11] showed the unit energy costs of gold mining range from 120 to 213 GJ/kg Au and averaged 143 GJ/kg Au. The unit energy costs for PGMs are higher than gold, but not as much as could be expected based on the differences in mining and processing. Overall, total energy consumption will largely be a function of PGM production.

The typical range for unit GHG emissions is 24.8 to 78.3 t CO_{2-e}/kg PGM, and an average of 39.4 t CO_{2-e}/kg PGM. The unit emissions costs for gold typically ranges from 10.3 to 16.4 t CO_{2-e}/kg Au and averages 11.5 t CO_{2-e}/kg Au [11]. The significantly higher unit emissions 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. If future electricity is sourced increasingly from renewables, this high emissions intensity could be reduced significantly without impacting on PGM production capacity.

In terms of water consumed in milling, the range in this study for processing PGM ore is 0.56 to 2.33 m^3/t milled, with one project at 12.6 m^3/t milled, and an average of 1.32 m^3/t milled (excluding the high value). The typical range for unit water consumption is 214 to 1,612 m^3/kg PGM, with an average of 391.5 m^3/kg PGM. The extent of water consumption for PGMs is within typical ranges for various metals, including gold, which ranges from 224 to 1,783 m^3/kg Au and averages of 691 m^3/kg Au [11,16]. This is not surprising, since many metal ores also undergo grinding and flotation to produce concentrates. An unexpected outcome is the degree to which some projects have reduced total consumption and improved water efficiency. For example, Lebowa has reduced water consumption from a high of 6.07 million m^3 in 2004 to just 284,000 m^3 in 2007. Unfortunately, the reasons for this are not explored in Anglo's sustainability reporting. Not all projects have been successful in this regard, however, 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 2007 despite similar production levels.

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. 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 [18]. 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 water discharge quality.

CONCLUSIONS

This paper has studied the platinum group metal 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 resources available, concentrated mainly in the Bushveld Complex of South Africa. The main question is therefore the environmental costs of PGM production. In this regard, the major factors apparent from this study include ore grade, large volume mine wastes, high electricity consumption and electricity source (ie. coal). Overall, the environmental costs of PGM production are significant but appear to be related mainly to production levels – and given the projected demand in the future, the cumulative environmental costs in such a concentrated region provide both a major challenge and opportunity with respect to sustainability.

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