

Platinum group metals: a unique case study in the sustainability of mineral resources

G.M. MUDD

Environmental Engineering, Monash University, Melbourne, Australia

Platinum group metals (PGMs) are used in a wide range of high technology applications, leading 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 production and 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, and economic aspects associated with this globally important industry? Many PGM companies have been at the forefront of sustainability issues in the global mining industry, and are arguably the leaders in such reporting. This paper synthesizes a unique combination of data which relate 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 mining sector—a sector which clearly has a bright future for decades to come.

Introduction

Platinum group metals (PGMs) possess a range of unique chemical and physical properties and are increasingly finding important uses in a variety of environmentally-related technologies—such as chemical process catalysts (especially oil refineries), catalytic converters for vehicle exhaust control, 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.

Global production of PGMs is dominated by South Africa due to their large 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; Yang, 2009), as well as allegations of significant environmental and social impacts such as water pollution, unfair village relocation, economic disparity and compensation issues (Curtis, 2008; Mnwana and Akpan, 2009; Rajak, 2008).

This paper presents a detailed review of the PGMs industry and major environmental costs such as water, energy and greenhouse gas emissions (GGEs). A range of data is 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 PGMs 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.

PGM resources, mining and production

Economic resources

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

- Stratiform deposits—where PGMs occur in large Precambrian mafic to ultramafic layered intrusions; 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 are usually considered primary due to their size (~10–1 000 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 (~10–1 000 Mt, 1–3 g/t PGMs, ~2–3% Ni+Cu).

- Ni-Cu bearing sills—related to rift structures, allowing concordant intrusive sheets; with examples being the Nor’ilsk-Talnakh District in Russia and the Jinchuan deposits in China (~10–1 000 Mt, 2–15 g/t PGMs, ~3–5% Ni+Cu).
- Placer deposits—alluvial sedimentary deposits containing coarse PGMs (mainly Pt).

A compilation of economic PGMs reserves and resources by mine and ore type is given in Table I for the eastern and western Bushveld Complex, with all other known PGM resources in Table II and Ni-Cu-PGMs in Table III. All data are derived from company annual reports (or other studies)

based on formal mineral resource reporting codes (e.g. Australia’s ‘JORC’ Code and South Africa’s ‘SAMREC’).

Based on data in Tables I to III, economic PGMs as of 2009 amount to at least 80 000 t PGMs. Of this amount, some 57 100 t PGMs is contained in the Bushveld Complex in South Africa, whereas Russia possesses some 13 300 t PGMs. According to (USGS, var.), South African, Russian and global PGM reserves (based on USGS terminology) are 63 000, 6 200 and 71 000 t PGMs, respectively—sufficiently close to data in the Tables.

Mining

The mining of PGM ores is through conventional underground or open cut techniques. The next stage is

Table I
PGM ore reserves and resources by mine and ore type in the eastern and western Bushveld Complex (2009 data)

	Ore Reserves						Ore Resources					
	Merensky Reef			UG2 Reef			Merensky Reef			UG2 Reef		
	Mt ore	4E g/t	t PGM	Mt ore	4E g/t	t PGM	Mt ore	4E g/t	t PGM	Mt ore	4E g/t	t PGM
Bathopele				51.1	2.87	146.7				0.3	3.94	1.2
Khomanani	9.9	5.85	57.9	10.3	3.54	36.5	10.4	6.61	68.7	36.4	5.48	199.5
Thembelani	20.4	5.52	112.6	14.0	4.15	58.1	5.8	5.68	32.9	54.7	5.53	302.5
Khuseleka	7.8	5.10	39.8	50.6	4.14	209.5	1.3	3.51	4.6	7.4	5.92	43.8
Siphumelele	10.4	5.88	61.2	23.8	3.79	90.2	10.3	7.61	78.4	64.6	5.63	363.7
Rustenburg Other							28.8	6.32	182.0	61.3	5.54	339.6
Tumela	35.9	5.94	213.2	168.9	4.87	822.5	158.7	7.16	1,136.3	198.0	5.60	1,108.8
Dishaba	22.7	5.65	128.3	98.9	4.81	475.7	32.5	8.18	265.9	44.6	5.87	261.8
Union	0.8	5.62	4.6	53.1	3.75	199.0	91.9	6.28	577.0	140.5	5.58	783.8
Twickenham				74.5	4.96	369.5	161.4	5.04	813.5	165.4	5.77	954.4
Modikwa				48.4	4.94	239.1	208.8	2.70	563.8	224.6	5.97	1,340.9
Kroondal				54.6	2.90	158.3				0.6	5.88	3.5
Maraikana PSA [#]				29.8	3.33	99.2				6.0	3.52	21.1
Maraikana (Aquarius)										15.1	5.09	76.8
Maraikana (Lonmin)										750.7	5.01	3,761.0
Mototolo				15.0	4.01	60.2				31.8	4.35	138.3
Bafokeng-Rasimone	78.8	4.27	336.5				112.6	6.88	774.7	206.2	5.34	1,101.1
Bokoni	24.1	4.44	106.9	41.6	5.44	226.5	145.7	5.65	823.3	314.1	6.78	2,129.5
Der Brochen	1.7	3.75	6.4				165.6	4.08	675.6	319.9	4.72	1,509.9
Ga Phasha							236.5	4.49	1,062.0	269.0	6.50	1,748.4
Pandora JV				8.9	4.25	38.0				147.3	4.25	626.0
Magazynskraal 3JQ							46.9	6.58	308.5	63.4	4.65	294.7
WBJV	18.1	5.45	98.7	11.4	3.40	38.6	18.4	5.91	108.6	25.7	4.80	123.2
Anglo Pt Other Projects										13.2	6.15	81.2
Northam (Zondereinde)							66.00	6.83	450.8	66.9	5.19	347.1
Booysendal							255.5	4.69	1,198.2	580.5	3.47	2,014.4
Townlands										1.57	6.30	9.9
Everest										34.3	3.38	116.0
Everest-Sterkfontein										13.0	3.50	45.5
Everest-Hoogland										6.6	2.88	19.0
Everest-Vygenhoek										2.77	5.11	14.2
Chieftains Plain							85.0	4.30	365.5	115.0	5.70	655.5
Walhalla							135.0	4.30	580.5	185.0	5.70	1,054.5
Impala							299.6	6.12	1,833.9	259	6.89	1,784.4
Marula							49.1	5.63	276.6	52.5	8.46	443.9
Afplats										399.8	4.89	1,955.0
Two Rivers							22.6	3.38	76.3	62.1	3.92	243.2
Tamboti							123.3	3.87	476.8	153.3	5.56	852.3
Limpopo										144.7	4.22	610.6
Limpopo Baobab Shaft										46.1	3.91	180.3
Loskop JV										24.7	4.04	99.9
Garatau							67.8	4.74	321.4	75.8	5.44	412.4
Tubatse							153.2	4.45	681.8	105.8	7.18	759.1
Roederand-Ruighoek										36.7	3.8	139.5
Kliprivier										109.6	2.3	252.1
Smokey Hills										4.64	5.11	23.7
Pilanesburg										118.0	3.00	354.3
Eland										159.6	4.33	691.4
Zilkaatsnek										4.16	2.4	10.0
Schietfontein										20.4	2.5	50.7
Grootboom										20.5	4.38	89.8
Mphahlele										121.4	3.93	476.6
Oorlogsfontein										47.0	1.11	52.1
Totals	230.6	5.06	1,166	754.9	4.33	3,268	2,693	5.10	13,738	6,132	5.07	31,072

Note: Resources are in addition to reserves. 4E = Pt+Pd+Rh+Au; [#]PSA – Production and Sharing Agreement.

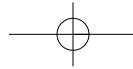


Table II
PGM ore reserves and resources by mine and ore type in the northern Bushveld Complex, Great Dyke and other global sites (2009 data)

	Ore type	Ore Reserves					Ore Resources				
		Mt ore	4E g/t	%Ni	%Cu	t PGM	Mt ore	4E g/t	%Ni	%Cu	t PGM
Mogalakwene	Platreef	508.6	3.20			1,628	2,268.5	2.00			4,537
Aknani	Platreef						176.6	3.96			699.3
Mimosa - North Hill	Great Dyke						48.6	3.64	0.14	0.11	176.9
Mimosa - South Hill	Great Dyke						88.3	3.77	0.14	0.12	332.9
Unki	Great Dyke	48.5	3.79	0.20	0.14	183.7	118.2	4.28	0.20	0.15	506.0
Zimplats	Great Dyke						1,880	3.64	0.13	0.11	6,843
Panton (Australia)	-						14.3	5.20			74.4
Pedra Blanca (Brazil)	-						12.9	2.27	0.23	0.03	29.4
Lac des Iles (Canada)	-						40.7	3.88	0.09	0.07	51.7
River Valley (Canada)	-						33.0	1.36	0.02	0.1	44.9
Kalplats (South Africa)	-						130.7	1.53			200.0
Stillwater (USA)	Stillwater						37.2	17.14			637.5
Totals	Platreef	508.6	3.20	-	-	1,628	2,445	2.14	-	-	5,236
Totals	Great Dyke	48.5	3.79	0.20	0.14	183.7	2,135	3.68	0.11	0.13	7,859
Totals	Miscellaneous	-	-	-	-	-	268.8	4.26	-0.03	-0.03	1,144

Note: Resources are in addition to reserves. 4E = Pt+Pd+Rh+Au.

Table III
Ni-Cu-PGM ore resources by mine (2009 data)

	Mt ore	3E g/t	%Ni	%Cu	t PGM
Tati (Botswana)	135.3	0.57	0.23	0.27	77.0
Shebandown (Canada)	1.5	1.20	0.93	0.62	1.8
Sudbury-Fraser Morgan (Canada)	8.6	0.32	0.32	0.55	2.7
Sudbury-Onaping Depth (Canada)	15.7	1.00	2.74	1.25	15.7
Vale Inco Sudbury (Canada)	116.9	2.3	1.20	1.51	271.5
Kingashskoye-Verkhnekingashskoye (Russia)	484.6	0.63	0.21	0.45	305.5
Kola Peninsula (Russia)	831.9	0.07	0.55	0.26	59.4
Maslovskoye (Russia)	215	6.53	0.33	0.51	1,404
Nor'ilsk-Taimyr Peninsula (Russia)	2,197.7	5.25	0.97	1.26	11,541
Mokopane (South Africa)	39.7	~0.6	0.15	0.09	23.8
Nkomati (South Africa)	408.6	0.85	0.33	0.13	349.1
Sheba's Ridge (South Africa)	688.6	0.90	0.18	0.07	619.7
Kabanga (Tanzania)	53.5	0.48	2.68	0.37	25.9
Totals	5,198	2.83	0.65	0.71	14,697

Note: 3E = Pt+Pd+Au.

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, whereas 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).

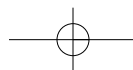
Production

A detailed compilation of PGMs production statistics by company, mine type and ore source is compiled in Table IV, with Ni-Cu-PGMs mines shown in Table V. Based on data from Tables IV and V, there is a wide array of project configurations, such as processing scale (from 0.13 to 11.63 Mt/year), ore grades (ranging from 2.5 to 19 4E g/t), lack of specific reporting of all PGMs by individual metal (commonly only 4E or Pt, Pd, Rh and Au are given, or total PGMs).

In terms of ore source, the main reef for southern Africa has now become UG2 (at ~60%), followed by Merensky (~24%), Platreef (~11%) and Great Dyke (~5%). Base

metal production (Ni-Cu), although generally small by individual mine, is moderate in aggregate, especially when compared to the Ni-Cu giants of Nor'ilsk and Sudbury.

A common concern raised over PGMs is the extent of remaining resources—or simply years left (e.g. (Gordon *et al.*, 2006; Yang, 2009). Based on 2009 production of ~450 t PGMs (Jollie, 2010) and some 80 000 t PGMs of resources, this gives 175 years remaining supply at present rates and based on conventional mining and processing technology. Alternatively, if a 4% growth in production is assumed, by 2060 annual production will have reached ~3 460 t PGMs/year with cumulative production ~80 000 t PGMs. At present, economic resources in the Bushveld are estimated to between only 1 to 2 km depth, although the Merensky and UG2 reefs are known to extend to several kilometres. In addition, there are other reef layers with lower grade PGMs which could be developed in future if conditions were conducive. Of course, production is most likely to continue to grow strongly over the medium to longer term, especially given the increasing demands for PGMs. The more critical and pressing issue is that there is a realistic supply challenge—Southern Africa has a major electricity generation crisis, with insufficient capacity to meet demands and major risks of brownouts or blackouts. For Norilsk in Russia, they are dominantly palladium but are suffering declining ore grades (comparing production in Table V to resources in Table III, ie. 8.06 v. 5.25 g/t).



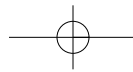


Table IV
Detailed PGMs production statistics of mines in the Bushveld Complex, Great Dyke and other global sites (2009 data)

Mine/Project	t ore milled	4E g/t	kg Pt	kg Pd	kg Rh	kg Ru	kg Ir	kg Au	t Ni	t Cu	Ore Source	Mine Type	Principal Owners
Bathopele ^a	2,962,000	3.08	4,155	2,298	805	-	-	47	300	100	UG2 ^{100%}	UG ^{100%}	Anglo Platinum ^{100%}
Khomanani ^a	1,274,000	4.92	3,281	1,474	345	-	-	143	700	500	UG2 ^{40%} , Mer ^{60%}	UG ^{100%}	Anglo Platinum ^{100%}
Thenbelani ^a	1,174,000	4.46	2,466	1,263	404	-	-	65	500	200	UG2 ^{81%} , Mer ^{19%}	UG ^{100%}	Anglo Platinum ^{100%}
Khuseleka ^a	2,344,000	4.28	4,883	2,364	684	-	-	162	1,000	500	UG2 ^{64%} , Mer ^{36%}	UG ^{100%}	Anglo Platinum ^{100%}
Siphumelele ^a	1,509,000	4.52	3,440	1,592	407	-	-	134	700	400	UG2 ^{56%} , Mer ^{44%}	UG ^{100%}	Anglo Platinum ^{100%}
Tumela ^b	4,202,000	4.51	9,137	4,155	1,459	-	-	183	1,100	500	UG2 ^{78%} , Mer ^{22%}	UG ^{100%}	Anglo Platinum ^{100%}
Dishaba ^b	1,866,000	4.95	4,668	2,093	594	-	-	152	900	500	UG2 ^{47%} , Mer ^{53%}	UG ^{100%}	Anglo Platinum ^{100%}
Union	5,517,000	3.50	9,078	3,959	1,536	-	-	140	900	400	UG2 ^{62%} , Mer ^{37%}	UG ^{100%}	Anglo Platinum ^{83%}
Bafokeng	2,148,000	4.53	5,365	2,143	370	-	-	305	1,700	1,000	UG2 ^{1%} , Mer ^{99%}	UG ^{100%}	AngloPt ^{33%} , RBH ^{67%}
Bokoni ^c	898,000	4.32	1,917	1,295	330	-	-	127	612	408	UG2 ^{38%} , Mer ^{62%}	UG ^{100%}	AngloPt ^{49%} , AnRes ^{51%}
Mogalakwane ^d	9,722,000	2.71	7,256	7,772	541	-	-	964	9,100	5,800	Platreef ^{100%}	OC ^{100%}	Anglo Platinum ^{100%}
Twickenham	130,000	4.62	233	224	50	-	-	6	0	0	UG2 ^{100%}	UG ^{100%}	Anglo Platinum ^{100%}
Modikwa	2,380,000	4.64	4,208	3,981	846	1,234	300	115	600	300	UG2 ^{99%} , Mer ^{1%}	UG ^{100%}	AngloPt ^{50%} , ARM ^{41.5%}
Mototolo JV	1,120,000	3.42	3,306	1,913	535	-	-	50	300	100	UG2 ^{100%}	UG ^{100%}	AngloPt ^{50%} , AqPt ^{50%}
Kroondal JV	6,482,000	2.57	7,791	3,845	1,428	2,330	553	63	429	186	UG2 ^{100%}	UG ^{99.9%} , OC ^{0.1%}	AngloPt ^{50%} , AqPt ^{50%}
Marikana JV	2,584,000	2.84	3,023	1,357	503	880	205	30	237	131	UG2 ^{100%}	UG ^{49.4%} , OC ^{50.6%}	AngloPt ^{50%} , AqPt ^{50%}
Everest	839,000	2.89	1,171	602	202	~400	~80	17	122	64	UG2 ^{100%}	UG ^{100%}	Aquarius Platinum ^{100%}
Mimosa	2,111,000	3.60	2,846	2,159	223	190	98	370	2,539	2,074	Great Dyke ^{100%}	UG ^{100%}	AqPt ^{50%} , Implants ^{50%}
Two Rivers	2,616,000	4.10 ^e	3,671	2,096	595	1,013	235	51	365	190	UG2 ^{100%}	UG ^{100%}	ARM ^{5%} , Implants ^{45%}
Northam	2,105,091	5.1	6,288	3,046	848	1,227	249	180	1,529	800	UG2 ^{50%} , Mer ^{50%}	UG ^{100%}	Northam Platinum ^{100%}
Implats	15,102,000	4.56	29,561	13,233	3,860	-	-	-	6,200	-	UG2 ^{55%} , Mer ^{45%}	UG ^{100%}	Implats ^{100%}
Marula	1,574,000	4.29	2,301	2,373	488	-	-	-	220	-	UG2 ^{100%}	UG ^{100%}	Implats ^{73%}
Zimplats	2,357,000	3.52	2,986	2,264	243	-	-	-	1,607	-	Great Dyke ^{100%}	UG ^{100%}	Implats ^{87%}
Crocodile River	1,696,839 ^f	4.1 ^f	2,031 ^f	898 ^f	345 ^f	619 ^f	145 ^f	16 ^f	-	-	Great Dyke ^{100%}	UG ^{100%}	Implats ^{87%}
Lommin	11,627,000	4.49	20,380	9,250	2,973	4,556	744	568	3,244	1,988	UG2 ^{78%} , Mer ^{22%}	UG ^{100%}	Implats ^{87%}
Eland	~1,200,000 ^g	~4.33 ^h	~2,482	~1,141	~391	-	-	-	-	-	UG2 ^{100%}	OC ^{100%}	Xstrata ^{100%}
Blue Ridge	>600,000	~2.5	>616	>306	>97	>178	>36	>10	-	-	UG2 ^{15%} , Mer ^{85%}	no data	Xstrata ^{100%}
Pilanesberg	~1,360,000 ^g	~3.0 ^h	861.0 (4E PGMs)			-	-	-	-	-	no data	OC ^{100%}	Platmin ^{72.4%}
Smokey Hills	~500,000 ^g	~3.4	879.0 (4E PGMs)			-	-	-	-	-	UG2 ^{100%}	UG ^{50%} , OC ^{50%}	Platinum Australia ^{79%}
East Boulder	369,200	13.0	964	3,266	124	-	-	280	388	352	Stillwater ^{100%}	UG ^{100%}	Norilsk ^{51.5%}
Stillwater	704,900	19.2	2,861	9,392	-	-	-	-	-	-	Stillwater ^{100%}	UG ^{100%}	Norilsk ^{51.5%}
TOTAL	91.1 Mt	4.05	~153.4 t	~92.3 t	~21.4 t	>>12,227	>>2,565	~4,178	35.3 kt	16.5 kt			

^aFormerly part of the RPM Rustenburg group; ^bFormerly part of the RPM Amandelbult group; ^cFormerly known as Lebowa; ^dFormerly known as Potgietersrust; ^eOre grade is 6E g/t PGMs; ^fore processed and PGMs production includes some tailings reprocessing (about 30% of material milled in 2009); ^gapproximate estimate only; ^hore grade assumed from reported resources. UG2 – upper group 2 reef ore; Mer. – Merensky reef ore; OC – open cut; UG – underground; AngloPt – Anglo Platinum; AqPt – Aquarius Platinum; RBH – Royal Bafokeng Holdings; AnRes – Anoroaq Resources; ARM – African Rainbow Resources.

Table V
Detailed Ni-Cu-PGMs production statistics of global mines (2009 data)

Mine/Project	t ore milled	%Ni	%Cu	kt Ni	kt Cu	PGMs g/t	kg Pt	kg Pd	kg Au	kg PGMs	Mine Type	Owners
Nokmati	1,976,000	0.51	0.23	6.01	2.87	0.44 ^a	187	684	-	871	OC, UG	Norilsk ^{50%} , ARM ^{50%}
Tati	10,709,000	0.25	0.24	17.4	13.4	0.34 ^a	529	3,110	-	3,639	OC	Norilsk ^{85%} , Botswana ^{15%}
Vale Sudbury	3,145,000	1.19	1.49	43.6	42.0	~2.7 ^a	3,203	4,727	1,524	~8,400	UG	Vale Inco ^{100%}
Taimyr Peninsula	15,298,000	1.52	2.55	196.0	364.4	8.06	19,780	83,224	-	103,004	UG, OC	Norilsk ^{100%}
Kola Peninsula	7,892,000	0.65	0.27	36.8	18.0	- ^b	- ^b	- ^b	-	- ^b	UG, OC	Norilsk ^{100%}
TOTAL	39.02 Mt	0.92	1.25	299.8	440.7	~3.5	23,699	91,745	1,524	115,914		

^aYield not assay grade; ^bPGMs production included in Taimyr Peninsula. OC – open cut; UG – underground; ARM – African Rainbow Resources.

The PGMs sector and sustainability

Overview

In the past decade, there has been a strong growth in annual environmental or sustainability reporting by numerous mining companies (Mudd, 2007, 2008, 2009), 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 availability of growing data-sets on mine wastes, energy, water and greenhouse gas emissions from sustainability reporting can be easily combined with production statistics. In this way it is possible to link these aspects with ore grade, ore type, annual throughput or project configuration, providing some useful benchmarks to compare individual site operations but also understand the environmental implications of PGM production, as well as valuable data for broader analyses of other mineral commodities or PGM-containing products.

This study focuses primarily on South African PGM projects, with some data from Zimbabwean projects. The 'sustainability metrics' used are unit consumption per PGM production (e.g. GJ/kg PGM, m³/kg PGM) with respect to

ore grade (4E g/t), unit consumption per tonne of ore milled (e.g. m³/t ore, GJ/t ore) with respect to mill throughput (Mt ore/year), and similarly for GGEs (e.g. t CO₂-e/kg PGM, t CO₂-e/t ore).

Results: sustainability metrics of PGMs

Summary results

The compiled results for sustainability metrics, including energy consumption by direct/indirect and by mine and processing stage, are given in Table VI. Although some projects only have a small number of years, both the general consistency and variability provide useful insights, discussed further below.

Water

Graphs of unit water costs versus throughput or over time, shown in Figure 1, 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,

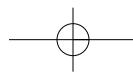


Table VI
Environmental sustainability metrics of PGMs production

Individual Project / Mine	Mining MJ/t rock	Milling MJ/t ore	Energy GJ/kg PGM	Energy MJ/t ore	Water m ³ /kg PGM	Water m ³ /t ore	CO ₂ Emissions 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)
Bokoni ^a (MC)	404 (2)	153 (2)	164 (7)	606 (7)	385 (7)	1.397(7)	39.4 (7)
Mogalakwane ^b (MC)	21 (2)	232 (2)	201 (7)	500 (7)	277 (7)	0.695 (7)	31.1 (7)
Amandelbult ^c (MC)	292 (2)	148 (2)	106 (7)	465 (7)	209 (7)	0.928 (7)	26.3 (7)
Rustenburg ^d (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)	-
Crocodile 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)	-
	Energy	Fraction					
Company / Group Totals	Direct	Indirect	GJ/kg PGM	MJ/t ore	m³/kg PGM	m³/t ore	t CO_{2-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-refinery; number of years of data in brackets. [§]Assuming coal is used in milling/smelting only and diesel is used in mining only. All data from respective company annual sustainability and financial reporting (up to 2008 data). ^aFormerly Lebowa; ^bFormerly Potgietersrust; ^cNow known as Tumela and Dishaba; ^dNow known as individual mines of Bathoepel, Khomanani, Thembelani, Khuseleka and Siphumelele.

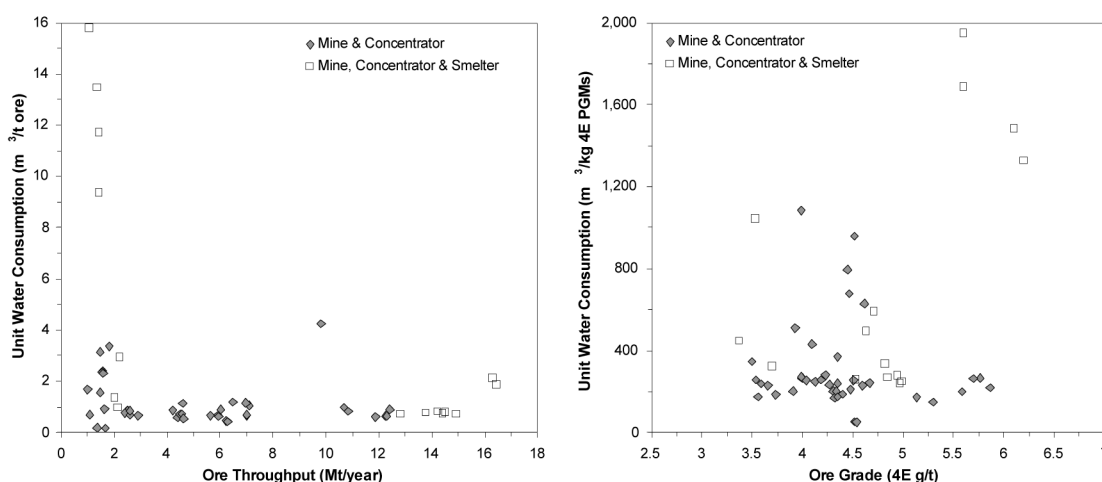


Figure 1. Unit water consumption versus ore throughput (left) and ore grade (right)

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.

Energy

Graphs of energy metrics in Figure 2 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. lower scales entail higher costs). Ore grade does appear to be significant for unit energy consumption (correlation coefficient 51.9%, Figure 2).

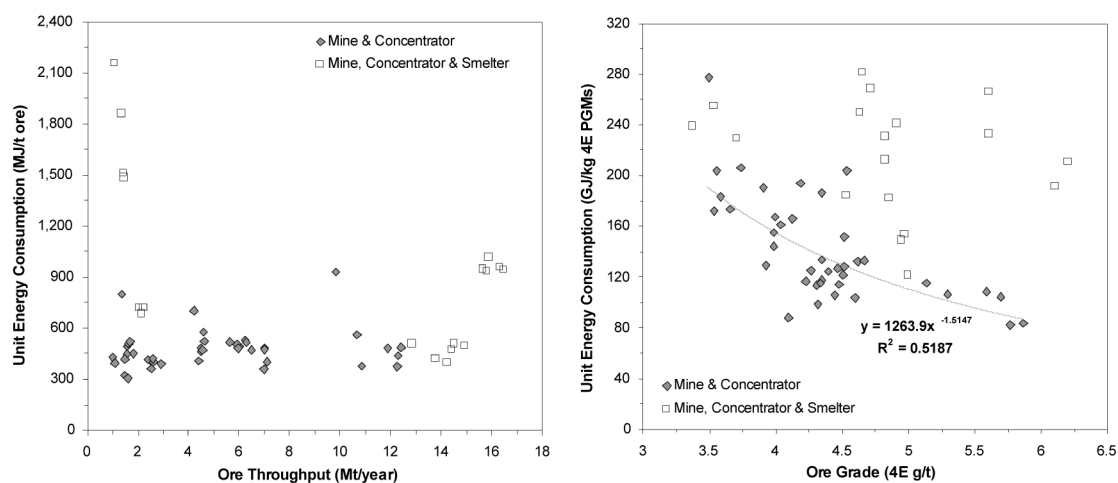


Figure 2. Unit energy consumption versus ore throughput (left) and ore grade (right)

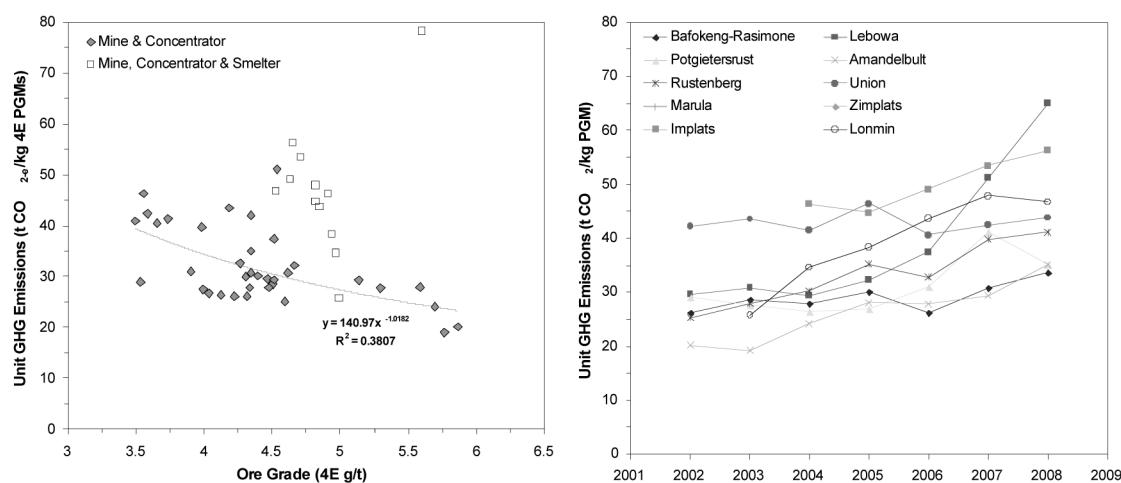


Figure 3. Unit greenhouse gas emissions versus ore grade (left) and over time (right)

No project studied has shown long-term energy efficiency improvements over time, with most showing relatively stable trends. The Bokoni (formerly 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 Mogalakwane (formerly Potgietersrust) (21 MJ/t rock) is due to this being an open cut mine, whereas the deep Northam underground mine (~2 km) has the highest mining energy consumption (1 244 MJ/t rock). The data in Table VI also show 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 producers have planned expansions to incorporate open cut mines in the future. Comparison of underground mines to the open cut Mogalakwane 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 requiring proactive assessment and management.

Greenhouse gas emissions

A moderate relationship is suggested between ore grade and unit GGEs (correlation coefficient 38.1%, Figure 3), whereas the correlation between unit energy and unit emissions, surprisingly, yields a correlation coefficient of only 63.4% (Figure 4)—despite South Africa’s electricity supply being dominated by coal (~90%) with a small proportion of hydroelectricity (~5%). The variability could be due to different estimation methods used by companies, although given the dominance of electricity this would not be 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 mostly show a gradually increasing trend for all projects included in Figure 3.

There is some evidence for major PGM producers showing declining ore grades over the past decade (data not shown), meaning that unit GGEs could begin to increase if no action is taken. Some PGM companies are now responsible for GGEs of the order of several millions of

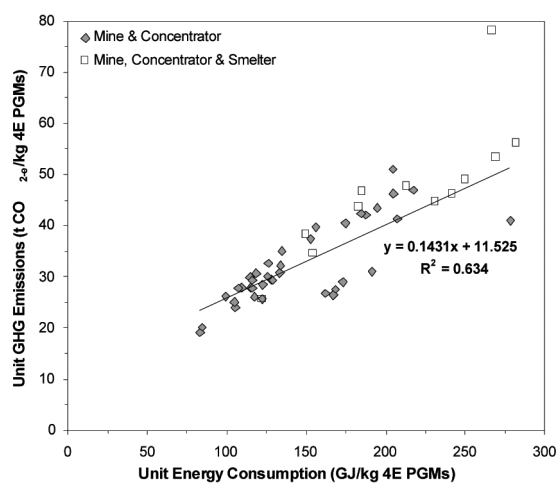


Figure 4. Unit energy costs versus unit greenhouse gas emissions

tonnes per year—and if development and production continues to grow at historical rates, this will lead to major increases in total emissions.

Based on Figure 4 and Table VI, the GGEs growth due to production increases is likely to be much greater than possible savings due to improved mine/mill/smelter efficiency. 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. electricity crisis). For example, some Anglo Platinum mines show variation within a typical range (e.g. Bafokeng, Union), whereas others show a gradual increase over time (e.g. Bokoni, Mogalakwane). 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.

Solid wastes—waste rock and tailings

The majority of PGM ore is sourced by underground mining, with 2009 production data showing that for the Bushveld, Great Dyke and Stillwater underground mining represents ~85% of the ore milled, with ~15% by open cut mining.

The large volumes of tailings and waste rock both 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 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 (e.g. 5 to 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 to 5:10. The waste:ore ratios reported for the Mogalakwane, Kroondal and Marikana Joint 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 sulphate—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 Mogalakwane). This highlights the importance of proactive management of large tonnage mine wastes, especially bordering large local communities which depend on the water resources adjacent to mining projects.

Conclusion

This paper has studied the PGM sector, compiling and analysing an extensive array of data on production, resources, wastes, 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 show 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 GGEs in PGM production. Although ore grades are not likely to decline significantly given that current projects are similar to known ore resources, this remains critical for individual projects but also the balance of different ores developed in the future (such as lower grade Platreef ores). 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 for sustainability. For PGMs, whether the environmental glass is half full or half empty is essentially in the eye of the beholder.

Acknowledgements

This paper is adapted and updated from previous work by Bonnie J. Glaister (since published in *Minerals Engineering*). Numerous PGM companies are commended for their commitment to sustainability and transparent public reporting, including requests for additional data or information. The research is independent, and the views of the author alone.

References

- AP, var., Annual Sustainability Report. Anglo Platinum Ltd (AP), Johannesburg, South Africa, Years 2002 to 2009, www.angloplats.com.
- CABRI, L.J. *The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of the Platinum-Group Elements*. Canadian Institute of Mining, Metallurgy & Petroleum, Montreal, Canada. 2002.
- CURTIS, M. *Precious Metal—The Impact of Anglo Platinum on Poor Communities in Limpopo, South Africa*. ActionAid, Johannesburg, South Africa, 2008. 57 pp.
- GORDON, R.B., BERTRAM, M., and GRAEDEL, T.E. Metal Stocks and Sustainability. *Proc. of the National Academy of Sciences*, 31 January, vol. 103, no. 5, 2006. pp. 1209–1214.
- JOLLIE, D. *Platinum 2010*. Johnson Matthey, England, May 2010, 64 pp.
- MNWANA, S.C., and AKPAN, W. Platinum Wealth, Community Participation and Social Inequality in South Africa's Royal Bafokeng community—A Paradox of Plenty? *Proc. SDIMI 2009 - 4th Int. Conf. on Sustainable Development Indicators in the Minerals Industry*, Australasian Institute of Mining and Metallurgy, Gold Coast, Australia, July 2009, pp. 283–290.
- MUDD, G.M. Global Trends in Gold Mining: Towards Quantifying Environmental and Resource Sustainability? *Resources Policy*, vol. 32, nos. 1–2, 2007. pp. 42–56.
- MUDD, G.M. Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining. *Mine Water and the Environment*, vol. 27, no. 3, 2008. pp. 136–144.
- MUDD, G.M. Sustainability Reporting and Mining—An Assessment of the State of Play for Environmental Indicators. *Proc. SDIMI 2009—4th Int. Conf. on Sustainable Development Indicators in the Minerals Industry*, Australasian Institute of Mining and Metallurgy, Gold Coast, Australia, July 2009, pp. 377–391.
- RAJAK, D. 'Uplift and Empower': The Market, Morality and Corporate Responsibility on South Africa's Platinum Belt. *Research in Economic Anthropology*, vol. 28, 2008. pp. 297–324.
- USGS, var., Minerals Commodity Summaries. US Geological Survey (USGS), Reston, Virginia, USA, Years 1996 to 2010, minerals.usgs.gov/minerals/pubs/mcs/.
- VAN NIEKIRK, H.J., and VILJOEN, M.J. Causes and Consequences of the Merriespruit and Other Tailings-Dam Failures. *Land Degradation and Development*, vol. 16, no. 2, 2005. pp. 201–212.
- VERMAAK, C.F. *The Platinum-Group Metals—A Global Perspective*. Mintek, Randburg, South Africa. 1995.
- YANG, C-J. An Impending Platinum Crisis and Its Implications for the Future of the Automobile. *Energy Policy*, vol. 37, no. 5, 2009. pp. 1805–1808.



Dr Gavin M. Mudd

Lecturer / Course Director – Environmental Engineering, Monash University

Dr Gavin M Mudd has been an active researcher and advocate on the environmental impacts and management of mining for over a decade. He has been involved with many aspects of industry with a particular specialty in brown coal wastes, uranium mining and environmental management. Gavin maintains an independent perspective, and has undertaken research for mining companies, community groups and indigenous organisations. With strong qualifications and experience, he has developed a unique understanding of the multidisciplinary nature of the environmental aspects of mining, culminating in a distinctive view on how to quantify an apparent oxymoron – that of 'sustainable mining'.